

BIPOLAR ELECTROKINETIC DEHYDRATION OF WOOD BY ELECTRO-OSMOSIS OF VARIOUS BREEDS

by

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In the article, the mechanism of electrokinetic's dewatering of wood electro-osmosis is considered. Models of a structure of a double electric-layer are considered. The electrokinetic way of wood dewatering is the most effective method. Its energy intensity is minimal. In given article results of experiments, bipolar electrokinetic's dewatering of wood of various species of wood is considered. The bipolar expiration of a liquid from wood is observed for use as a material of the anode of the titan, aluminum, tin, lead, and the alloys containing these materials. Most effectively wood dewatering is made across fibers. The speed of wood dewatering depends on intensity is established.

Key words: *drying, dewatering, dehydration, impregnation, electro-osmosis, electrodes*

Introduction

The phenomenon of the electro-osmosis water movement relatively rigid skeleton of the capillary from the anode to the cathode is long been known. When fluid moves along the wood capillaries quickly dehydrated anode region and the process is terminated at a high average moisture content of the wood. The bipolar outflow of fluid filling the pore space hetero capillary systems can occur when you create along their length regions with different signs electrokinetic potential [1]. Changing the sign of zeta potential, along the length of the diaphragm is achieved by creating non-equilibrium concentrations of products of electrochemical reactions occurring at the electrodes. Expiration bipolar process can only be observed when using certain materials as electrodes [2].

For the first time the phenomenon of migration through the pore space of the capillary-porous media caused by an external electric field imposed on the diaphragm was discovered by a professor at Moscow University Reuss [3]. This phenomenon is called electro-osmosis, which is defined as the movement of the fluid with respect to the solid skeleton by the electric field in the direction determined by the sign of zeta potential [3-6].

In the case of electro-osmosis, charges of opposite phases lead to the displacement of a constant electric field of mobile counter ions together with the liquid phase of the corresponding pole of the current source. Electro-transfer fluid through the pore space of the capil-

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lary-porous body is determined by the electrokinetic potential and the structure of the electrical double-layer at the phase boundary section [3, 4, 6, 7].

Method

Modern understanding of the mechanism of electrokinetic phenomena is based on the idea of the existence of the electric double-layer at the at the phase boundary section. On the surface of the solid dielectric according to the nature of the ionic double-layer solution ion pairs (dipoles) are exist. These pairs are able to orient in a certain way in relation to the phase boundary section. A layer of oriented dipoles at the phase boundary section is the electrical double-layer. This layer without being diffused can induce secondary diffuse-layers extending into the interior of the two phases on either side of the interface.

Charge ion double-layer is determined an excess of ions of the same sign in the structural geometry unit. The surface excess of ions is the difference which exists between the amount of volume of the ion, including surface area and the amount that would have been if it were completely homogenous phase dividing up their borders. Movement of the diffuse-layer of ions under the electric field due to internal friction entrains all the liquid mass filling the capillaries, fig. 1.

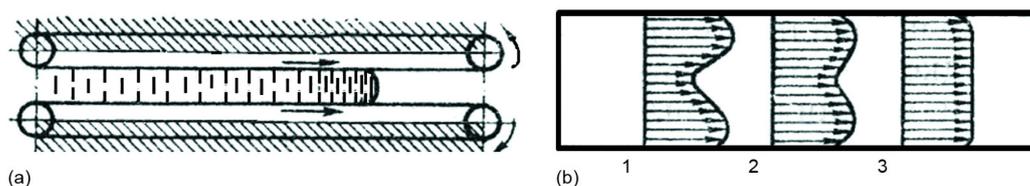


Figure 1. Electro-osmosis (a) fluid motion scheme under the influence of an electric current, (b) curves of speed; 1, 2, 3 – stages diagrams of curves of speed changes along the length of the capillary

The rate of motion of the liquid is determined by the formula:

$$v_{\ell} = v_r + \frac{I \varepsilon \zeta}{4\pi^2 \eta \chi r^2} \quad (1)$$

and the volume motion speed will be equal to:

$$v_0 = \frac{I \varepsilon \zeta}{4\pi \eta \chi} \quad (2)$$

where I [A] is the current, η [s] – the viscosity of the fluid, v_{ℓ} [ms^{-1}] – the electro-osmotic linear speed, v_r [ms^{-1}] – the hydrostatic speed, v_0 [ms^{-1}] – the electro-osmotic speed bulk, r [mm] – the radius of the capillary, ε [Fm^{-1}] – the dielectric constant, χ [$\text{mkSm}(\text{sm})^{-1}$] – the conductivity fluids, and ζ [mV] – the zeta potential.

There are a number of reasons, depending on the nature of the adjacent phases, leading to the emergence of potential jump at the boundary of the phase section [8]. One of the causes of the electrical double-layer is the exchange of charged particles, which at the moment of contact between the phases occurs predominantly in any one direction. As a result, an excess of particles of one charge on one side of the interface and the other disadvantage. As the potential difference between the phases, arising due to such an exchange, the

particle transfer speed in both directions is aligned. Equilibrium between the phases in contact, characterized by equality of electrochemical potentials of the particles $|\bar{\mu}_i|$, in both phases are advanced [3, 4, 9].

The second reason for the formation of the electrical double-layer, typical phase interface of gas-liquid, can be a selective adsorption of certain ions sign near the interface. In this case, one of the phases is impermeable to ions, and the potential drop in one of the localized phases.

The third reason, which leads to the formation of the electrical double-layer, may be the ability of polar uncharged particles oriented adsorbed near the phase interfaces. When adsorption oriented dipoles are oriented in one end side of the interface towards other phases belongs to the molecule. The magnitude of the potential that arises in this mechanism of formation of the electrical double-layer, determined by the number of adsorbed molecules and their dipole moments and the degree of dipole orientation.

The first structural model of the electrical double-layer, allowed to explain the existence of electrokinetic phenomena and quantify the capacity of the electrical double-layer has been proposed by Helmholtz [10].

Helmholtz [10] suggested that the electric double-layer capacitor is similar to a plane, *i. e.*, it consists of two layers of charges of opposite sign which are apart by a distance equal to the diameter of a water molecule, in which both layers were assumed to be uniformly charges *smearred*. Potential drop within the electrical double-layer was assumed to be linear. A major shortcoming of the theory of the structure of the electrical double-layer, proposed by Helmholtz, is that it is not possible to explain the experimentally observed dependence of the parameters of the electric double-layer on the electrolyte concentration and temperature. The theory that explains the relationship of the electrical double-layer parameters on the concentration of the electrolyte solution and the temperature was developed by Gouy L. and independently by several later D. Chapman [11, 12, see also in 13].

In addition to the electrical interaction of ions with a solid surface, Gouy and Chapman took into account the thermal motion of the ions. The authors started from the assumption that the surface of the phase section, as in any part of the solution there is a free thermal motion of the ions, but suggested that due to the presence of an electric field created by charges of a solid surface, the distribution of cations and anions near the phase interface is not the same.

The main disadvantage of Gouy-Chapman theory is that it does not take into account the finite size of ions, on the need to address that first pointed Stern [14]. The most recent work uses a modified Stern Gouy-Chapman theory, which takes into account the presence of ions of finite size. According to this theory, an electric double-layer composed of an inner electrode, representing a solid surface, and the outer electrode is divided into two layers: a dense-layer of ions directly close to the solid surface and the diffusion layer.

The structure of the dense-layer is defined by the presence of the ion hydration shells or partial dehydration of the ion. The thickness of the dense bed is defined as the distance from the center of gravity of the inner liner charges to a plane passing through the centers of the nearest to the surface of counterions called the plane of closest approach. The distribution of ions in the diffusion-layer is determined by two opposing factors: the electrostatic attraction, holding at the counter surface and diffusion equalizing their concentration in the surface layer and volume.

The potential drop in the outer plate of depending on the distance from the inner lining is shown in fig. 2. This relationship is linear only in a dense-layer of the outer electrode,

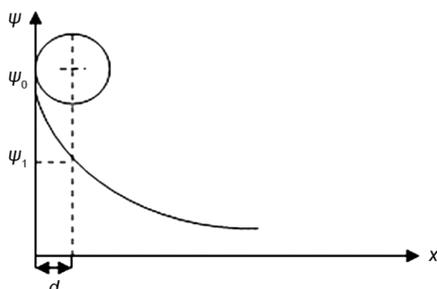


Figure 2. The potential distribution in the electric double-layer

change is not linear. Depending on the expression of the form:

$$\frac{d\psi}{dx} = -\sqrt{\frac{8\pi RT}{\varepsilon} \left(e^{\frac{zF\psi}{2RT}} - e^{-\frac{zF\psi}{2RT}} \right)} \quad (5)$$

where F [Kmol^{-1}] is the Faraday number, R [$\text{Jmol}^{-1}\text{K}^{-1}$] – the gas constant, T [K] – the temperature in degrees, ε [Fm^{-1}] – the dielectric constant, and z [–] – the ion charge.

From the condition of electrical and Poisson's equation can be an expression for the surface charge density as a function of the potential:

$$\eta_0 = \sqrt{\frac{2\varepsilon RT_c}{\pi}} \text{Sh } \gamma_1 \quad (6)$$

where $\gamma_1 = zF\psi_1/2RT$ is the dimensionless potential $\psi_1 = \psi$ and $x = d$.

Gouy equation takes into account only the Coulomb interaction of ions with counterions inner liner. To derive the equation in the case of non-Coulomb interaction, which takes into account the specific adsorption, Stern introduces the concept of ion, Φ_i , adsorption capacity of expressing the change in the potential energy of the system when transferring i of substance ions in the surface-layer of the depth of the solution, in the absence of an electric field.

The condition of electrical neutrality discussed in the Stern case has the form:

$$-\eta_0 = \eta_1 + \eta_2 \quad (7)$$

where η_1 is the charge density in a dense-layer that is called in the case of specific adsorption layer Stern, and η_2 – the charge density in the diffusion-layer.

The expression for the charge density in the diffusion-layer was obtained by Stern from the assumption that the ion adsorption obeys Langmuir isotherm, and the work volume of the ion transport in solution on a plane $x = d$ expressed by the relation:

$$W_i = \Phi_i + z_i F \psi_1 \quad (8)$$

On the basis of the linearity of the potential fall in a dense-layer, Stern received the following expression for the charge density in a dense-layer:

since, if it is assumed that the charge is concentrated in the center of the ion, the layer thickness, d , no charges hence from Poisson's equation:

$$\frac{d^2\psi}{dx^2} = 0 \quad (3)$$

it follows:

$$\frac{d\psi}{dx} = \text{const.} \quad (4)$$

When $x \geq d$ there is a space charge region in the diffusion layer, and that varies with the

$$\eta_1 = 2dzFc \left(e^{\frac{\Phi_+ + zF\psi_1}{RT}} - e^{\frac{\Phi_- - zF\psi_1}{RT}} \right) \quad (9)$$

The value η_2 corresponds to eq. (6) with the opposite sign. Thus, the final expression for η_0 is given by:

$$\eta_0 = 2dzFc \left(e^{\frac{\Phi_+ + zF\psi_1}{RT}} - e^{\frac{\Phi_- - zF\psi_1}{RT}} \right) + \sqrt{\frac{\epsilon RT_i}{2\pi}} \text{Sh} \gamma_1 \quad (10)$$

The theory, developed by Stern, yielded a good agreement between the theoretically calculated and experimentally measured data of the electrical double-layer. In particular, the transfer characteristics calculated curves experienced differential capacity curves [14].

A major shortcoming of the formula Stern is its inconsistency in the absence of specific adsorption. In the absence of specific adsorption forces of all the ions must be equivalent and be in the diffusion layer, and hence the eq. (9) shall apply to 0. However, if the expression $\Phi_+ = \Phi_- = 0$ (9) is not equal to 0. Ions in terms of the first layer (10) counted twice [15] since the diffusion layer includes the outer electrode all ions except specifically adsorbed. Therefore, for small values of the adsorption potential, it is considered appropriate to apply the eq. (6).

Contradictions theory Stern eliminated in the electric double-layer structure of the theory proposed by Graham [see in 3, 13], but developed Graham presentation, are very effective in treating complex cases together in a dense-layer of the adsorption of cations and anions, very significant in the study of metal-solution of the border.

A number of studies [16, 17] observed a significant efficacy of electro-drying walls, quartz sand, drying peat, in the construction of dams and other waterworks, when they built an alluvium soil of the ponds.

Results

The experiment revealed that in the case of Cu as the anode, carbon, stainless steel, iron-nickel alloys transfer fluid to the anode was observed. The liquid outflow occurs only to the cathode. After termination of the process, along the length of the sample was uneven moisture distribution - moisture grew in the direction from the anode to the cathode, fig. 3. Figure 3(a) is a part of fig. 3(b).

Termination of the dewatering process, in this case, is due to the drying of the cathode region due to the removal of fluid from it. The electrical resistance of dry wood is much higher than raw, so increasing the resistance of wood leads to the almost complete cessation of the drying process. Experiments show that some growth after current drops abruptly be-

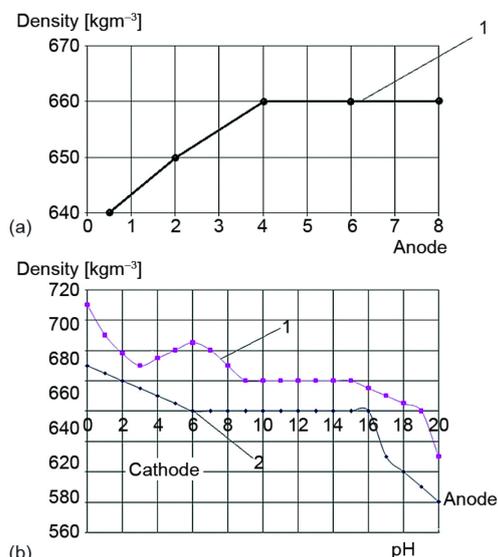


Figure 3. Distribution of wood density and pH along the length of the samples (the material of electrodes: anode - copper, cathode - tin); (a) in the anode part, (b) the entire length of the sample; 1 - the density of the samples, 2 - the solution pH

comes zero. We used samples of wood of different moisture. At high average moisture of the sample is 70% the process stops.

The increase in current through the diaphragm is explained by a slight increase in the number of carriers in the pore space of the capillary-porous body associated with electrochemical reactions at the electrodes.

The bipolar outflow of fluid from the timber is observed when using as the anode material of titanium, aluminum, tin, lead and some alloys containing these materials: duralumin, tungsten carbide and titanium alloy, tin-lead alloys.

When using these metals occur fluid outflow to both electrodes. But the relationship between the amount of fluid flowing to the anode and the cathode varies depending on the metal and the anode is estimated efficiency factor $K = V_a/V_k$, equal to the ratio of volumes of liquids emanating V_a to the anode, and the cathode V_k . Investigation of the amount of fluid flowing from pine samples at a field strength of 15 V/cm showed the following values of coefficients anode activity, tab. 1.

For tin-lead anode and cathode fluid amount flowing to the anode, it was five times smaller than the cathode. It can be assumed that the position of metals due to their adsorption capacity. It is known that the ion adsorption ability increases with its charge, and for the differently charged ions increases with decreasing radius hydrated current.

Table 1

Anode	Titanium	Aluminum	Tin	Lead
lead	1.1...0.75	0.5	0.5...0.3	0.2

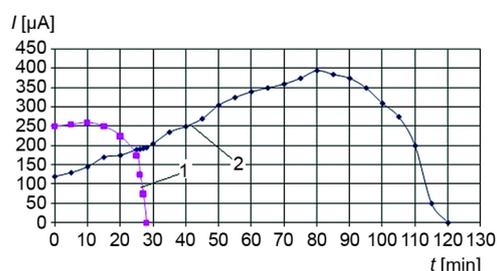


Figure 4. Dependence of the current time of dehydration; 1 – anode Cu, cathode-tin, 2 – the anode-tungsten carbide alloy and titanium, cathode-tin

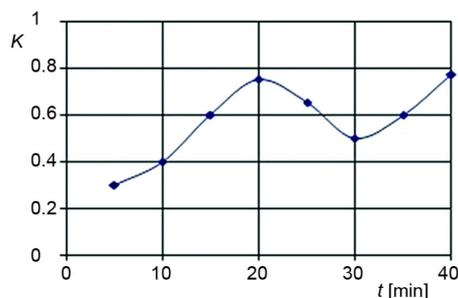


Figure 5. The dependence of the efficiency of the anode from the time

Aluminum and titanium are large negative values of the standard electrode potential, and it can be assumed that their ions in aqueous solutions exhibit its highest valence.

A characteristic feature of the current curve from the time when the tension strength of 20 V/cm is longer current passing through the pine sample compared to experiments, when the Cu electrodes (fig. 4, curve 1) was used as the anode.

This is due to the presence of the liquid component of the transfer to the positive pole of a current source, which prevents drying of the anode portion of the sample. This final moisture content of the samples after the termination of the process was about 28-30%. The limit of hygroscopicity of wood equals to 30%.

Experiments have shown that the current density flowing through the sample in bipolar after the change over time: first increases, reaches a maximum and then decreases. The linear dependence of the current density of the applied voltage is performed only during the initial period and during the current reaching a maximum. In the remaining periods of time Ohm's law does not hold for the sample. Moreover, there is the dependence of

the conductivity of the sample field. Along with the change of the current density flowing through the sample, the dependence of the anode efficiency ratio from time to time, fig. 5.

We have conducted experimental studies of electrokinetic dehydration of wood samples of different species. The results are presented in tab. 2. The results agree well with the theoretical concepts of the mechanism of bipolar outflow of a liquid from the pore space of the wood samples.

Table 2

Characterization of samples			Dehydration mode			Density, [kgm ⁻³]		Number of extraction liquid*		
Breed	Dimensions, [cm]		Quantity, [pcs]	Voltage, [V]	Tension [Vcm ⁻¹]	Dehydration time, t, [s]	Primary density	Ultimate density	[ml]	[kgm ⁻³]
	Length	Section								
Larch	6	2 × 2	5	1200	200	15	1000	690	–	310
	10	2 × 2	15	2000	200	18	860	690	–	170
	15	2 × 2	5	2000	133	20	950	720	–	230
	14,5	4 × 2	5	1000	70	125	950	740	–	210
	18	4 × 3	3	1000	55	140	980	720	–	260
	10	2 × 2	15	2000	200	30	850	720	–	130
	10	2 × 2	20	1000	100	45	750	660	–	90
	10	2 × 2	20	2000	100	45	760	650	–	110
Pine	50	d = 5 – 18	5	1000	20	2400	–	–	300	–
	50		5	400	8	1500	880	640	–	0,190
	80		3	800	10	5400	890	620	460	0,270
Birch	50		10	800	16	3000	860	610	–	0,250
	45		5	1000	22	1200	–	–	180	–
	30		5	1200	40	1800	–	–	230	–
	30		5	400	13	1800	–	–	120	–
	30		5	600	20	1800	710	580	–	0,130
	50		10	1200	24	4200	–	–	85	–
Spruce	50		10	1000	20	6600	–	–	250	–
	50	3	800	16	1800	–	–	250	–	
	80	5	1200	15	6000	–	–	435	–	

* The results of the analysis of the extract extracted from larch: dry residue (% by volume): 15.6 cathode, anode 21.1; resinous content (% of dry residue): 41.1 cathode, anode 28.2; the total content of resinous substances (% liquid volume) of 6%.

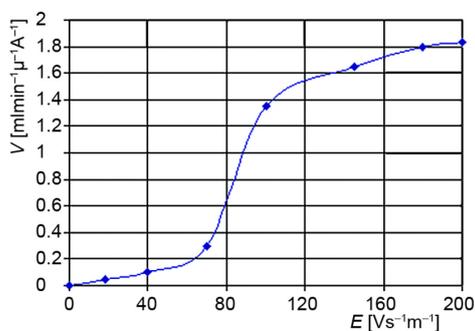


Figure 6. Dependence of the amount of fluid flowing out of the field strength for larch sample

Shown in fig. 6 data on the amount of fluid flowing from the field indicate that the linear relationship between the intensity of the fluid transfer and the value of the electric field strength, calculated at the Helmholtz-Smoluchowski equation is not satisfied.

Since the experimental results agree with the review mechanism of occurrence of bipolar expiration, in which the anode and cathode components are an electro-transfer character, to explain the fact of non-linearity of the transfer speed of the tension can use research Bondarenko [18], who discovered electro-dependency ratio of the field strength. Research has shown that dehydration is not performed most efficiently

along the fibers, and across, especially when handling the piece of round timber. In this case, at high field strengths (but at a low power consumption and a relatively low voltage) can be one-two order to reduce dehydration time [19]. When an electric field along the fiber resistance to movement will be less, but the make-up conditions, fig. 7, more difficult as the feed moisture from the side then must travel long capillary forces [20, 21].

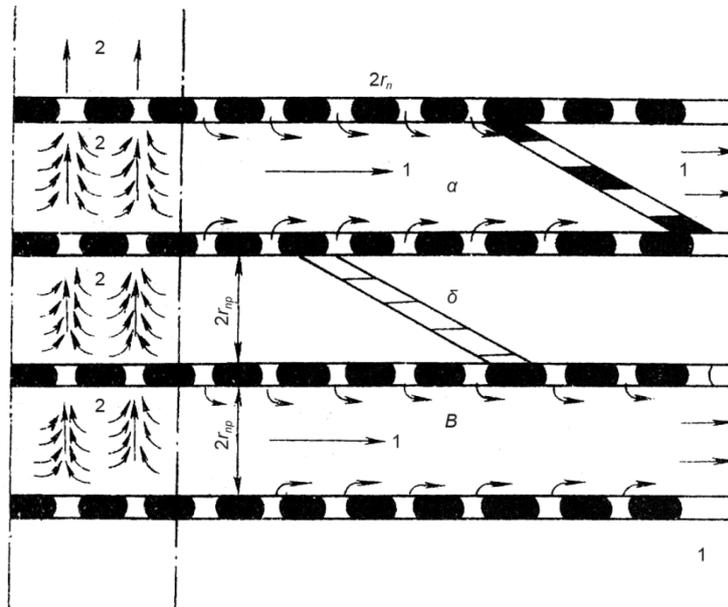


Figure 7. Scheme of movement and feeding conditions of the longitudinal and transverse capillaries; 1 – flow along the fibers, 2 – for across the grain; a, B – tracheids open, b – blind tracheids

In the case of applying an electric field across the fiber, resistance increases as the radius less improved but supplemented condition, since the pores are large lateral dimensions.

Therefore, the intensity of the dewatering in the longitudinal and transverse directions will be determined by structural parameters of the capillary-porous body.

Since the possibility of increasing the transverse direction is substantially greater field strength when a relatively small voltage source can obtain the necessary dewatering velocity in this direction.

Thus, the experimental results led to the following conclusions:

- Confirm the mechanism of bipolar outflow of a liquid from the wood: wood in the capillaries can be two separation mechanism of the solution to the components (redistribution of substances as a result of various values of the chemical potential of the molecules in the alkaline and acidic environments or changes in surface potential jump mark).
- Install the basic process patterns.

Conclusions

- The effect of the bipolar fluid outflow from timber depends only on the anode material and does not depend on the species.
- Dewatering timber can be at a field strength greater than 8 V/cm.
- Dehydration speed depends on the field strength: the higher the voltage, the process is more intense.
- The power consumption of current during dehydration cross-sectional area is proportional to the sample and the field strength (for example, 100 V/cm current density of 2 mA/cm² on average).
- If any initial moisture content samples dehydration process ends when humidity 22-70%.
- The moisture distribution along the length of the sample after the liquid in bipolar mode is in any one of the same nature and – at least part of moisture in the sample and the average increase in moisture to the ends.
- The coefficient of efficiency of the anode is 0.2-1.1, depending on the material.
- The calculated specific energy consumption according to the type and size of timber being processed is 0.011-0.11 kW/kg moisture removed.

References

- [1] Pouraria, H., et al., New Methods to Cope with Temperature Elevations in Heated Segments of Flat Plates Cooled by Boundary Layer flow, *Thermal Science*, 20 (2016), 1, pp. 45-52
- [2] Selimefendigil, F., Mixed Convection Boundary-Layer Flow of a Micro Polar Fluid Towards a Heated Shrinking Sheet by Homotopy Analyses Method, *Thermal Science*, 20 (2016), 1, pp. 21-34
- [3] Reuss, F. F., A Note on the New Action of Galvanic Electricity (1808), in: *Selected Works on Electricity*, Gos. Izd-vo Tehniko-Teor. Liter., Moscow, USSR, 1956, pp. 159-168
- [4] Fridrikhsberg, D. A., *Kurs kolloidnoi khimii*, (Course of Colloidal Chemistry – in Russian), Khimiya, Len-ingrad, USSR, 1974
- [5] Grigorov, S. N., *Electrokinetic Phenomena*, Moscow, USSR, 1973
- [6] Kroyt, G. R., *Science about Colloids*, Moscow, USSR, 1955
- [7] Adam, N. K., *Physics and Chemistry of Surfaces*, Moscow, USSR, 1947
- [8] Kammuang-Lue, et al., Effect of Working Fluids and Internal Diameters on Thermal Performances of Vertical and Horizontal Closed-Loop Pulsating Heat Pipes with Multiple Heat Sources, *Thermal Science* 20 (2016), 1, pp. 77-87
- [9] Antropov, L. I., *Theoretical Electrochemistry*, High School, Moscow, USSR, 1975
- [10] Helmholtz, H. A., Studein über elektrische Grenzschichten, *Ann. Phys.*, pp. 337-382, *Physic and Chemie*, Moscow, USSR, 1879
- [11] Gouy, M. G., Sur la constitution de la charge electrique a la surface d'un electrolyte, *J. Phys. Radium* (1910), pp. 457-468
- [12] Chapman, D. Al., A Contribution to the Theory of Electrocapillarity, *Philos. Mag.* 6 (1913)

- [13] Damask, B. B., Petery, O. A., *Introduction to Electrochemical Kinetics*, Moscow, USSR, 1975
- [14] Stern, O., Zur Theorie der elektrolytischen doppelschicht, *Zeitschrift für Elektrochem.*, 30 (1924), 508
- [15] Frumkin, A. N., et al., *Kinetik's Boars of Electrode Processes*, Moscow, USSR, 1952
- [16] Patyakin, V. I., *Problem of Increase of Buoyancy of Round Forest Products*, Leningrad, USSR, 1976
- [17] Sokolova, V. A., et al., To the Question about the Mechanism of Electrokinetic Dehydration of Wood – Electro-Osmosis, *Bulletin of Krasnoyarsk Agrarian University*, 12 (2009), 39, pp. 192–196
- [18] Bondarenko, N. F., *Study of Electro-Osmosis in Clay Soils in Connection with the Problem of Regulation of Their Construction and Properties*, Leningrad, USSR, 1996
- [19] Karabulut, K., et al., Performances of Packed Bed Double Pass Solar Air Heater with Different Inclinations and Transverse Wire Mesh with Different Intervals, *Thermal Science*, 20 (2016), 1, pp. 175-183
- [20] Sokolova, V. A., et al., The Results of Experimental Studies of Bipolar Electrokinetic Dewatering of Wood of Various Breeds, *Bulletin of Krasnoyarsk Agrarian University*, 1 (2010), 40, pp. 140-144
- [21] Sokolova, V. A., et al., Studies of Unipolar and Bipolar Electro-osmotic Treatment, *Bulletin of Krasnoyarsk Agrarian University*, 6 (2011), pp. 152–155