THE STUDY ON THE INFLUENCE OF THE ELECTROHYDRAULIC EFFECT ON THE DIFFUSION COEFFICIENT AND THE PENETRATION DEPTH OF SALT INTO MUSCLE TISSUES DURING SALTING

N. P. Oboturova*, I. A. Evdokimov, A. A. Nagdalian, Yu. I. Kulikov, O. A. Gusevskaya

North-Caucasus Federal University,
Pushkin Str. 1, Stavropol, 355000 Russian Federation

* e-mail: geniando@yandex.ru

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Abstract: Currently, promising methods for intensifying the salting technology of raw meat are those based on pulsed energy effects, accompanied by a variety of physical and chemical effects. One of these methods is a discharge-pulse technology, developed by the scientists of the department of meat and canning technologies of the North Caucasus Federal University. When a short high voltage electrical pulse forms in the brine-meat system, high pressure forms in the working tank, the increase in pressure is accompanied by a set of physical and chemical phenomena, such as ultrasound and electromagnetic radiation, ultraviolet glow, cavitation, etc. Taken together, all these phenomena have a beneficial impact on both the brine and the meat itself, accelerating the process of salting. In the present study, we tried using the method of determining the diffusion coefficient of salt in beef muscle tissues empirically by creating a concentration difference in two communicating chambers, the liquids in which are separated by the studied raw material of a given thickness. The main goal of the work was to evaluate the effectiveness of the discharge-pulse technology of salting meat raw materials by determining the NaCl diffusion coefficient and the penetration depth of salt into meat samples. The experimental results showed that with the discharge-pulse treatment of meat, the penetration rate of salt into muscle tissue increases and is proportional to the number of pulses transmitted to the system. The diffusion coefficient in test samples was higher that in the control meat samples at each time period. Based on the obtained results, we came to the conclusion that the discharge-pulse meat treatment contributes to the intensification of diffusion osmotic processes in the wet salting technology.

Keywords: Electrohydraulic effect, pulsed discharges technology, the diffusion coefficient, meat salting

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INTRODUCTION

Meat salting is a major operation in the salty piece goods technology and is carried out to achieve the desired organoleptic characteristics, inhibition of microbiological spoilage, meat maturation, give meat such important properties as tackiness, plasticity, high moisture content [1]. Three classic methods underpin all the various options of meat salting: dry (dry salting mixture), wet (with brine) and mixed. With any method of salting, the mass exchange occurs between the salting substances and soluble components of the product in the forming system of "brine-meat". With the dry salting, in the beginning, due to the hygroscopic qualities salt and moisture in raw materials, brine is produced. Upon contact of salt with the surface of raw material, the exchange diffusion occurs between them, which leads to a redistribution of salting substances, water and soluble components of the product. Penetration of salt into the tissue and the redistribution between tissues and brine occurs in at least two ways:

– osmotically, through membranes, covering the outer surface of the treated part of the tissue;

– through a system of macro- and micro-capillaries penetrating the tissue in all directions, followed by subsequent salt and water redistribution between this system and the cellular elements of the tissue.

At the same time, the penetration of salt in the second way occurs firstly and at a higher rate [4]. With the wet salting of raw materials, salt and water redistribution consists of three simultaneous processes:

1. Water and salt redistribution between the brine and the product.
2. Water and salt redistribution in the brine.
3. Water and salt redistribution in the product.

All three processes of water and salt redistribution occur in a diffusion-osmotic way. This suggests that despite the complexity of salting in detail, the kinetics of the process can generally be described by the equations adopted to describe diffusion processes [7].

In case of an isotropic environment, the second law of Fick describes the exchange diffusion:

$$\frac{dc}{d\tau} = D\frac{d^2c}{dx^2}, \quad (1)$$

where c is the concentration of diffuse substances, %; τ is the duration of the process, seconds; D is the diffusion coefficient of substances in water, m^2/s; $\frac{d^2c}{dx^2}$ is the concentration gradient towards diffusion.

However, meat is an anisotropic composite material, formed by a volumetric combination of chemically dissimilar colloidal components. In anisotropic bodies, the diffusion coefficient is a function of the crystallographic direction. In this case, D is no longer a "scalar" and becomes a tensor by its geometrical properties, i.e. the diffusion occurs by each coordinate axis with its diffusion coefficient D_x, D_y, D_z. Accordingly, for the non-stationary process, which occurs in three dimensions, the rate of diffusion will be determined by the Fick equation which is more complex:

$$\frac{dc}{d\tau} = D\left(\frac{d^2c}{dx^2} + \frac{d^2c}{dy^2} + \frac{d^2c}{dz^2}\right), \quad (2)$$

where $\frac{d^2c}{dx^2} + \frac{d^2c}{dy^2} + \frac{d^2c}{dz^2}$ is the Laplace operator.

In the brine-meat product heterogeneous system, the distribution process of salting substances depends on the value of resistance, offered to the diffusion flux by the meat product tissues. The permeability coefficient serves as a criterion for the process. The value of this indicator depends on specific salting conditions: parameters of brine and properties of raw meat. The quantitative ratio between the permeability of muscle, connective and adipose tissues is about 8 : 3 : 1. Therefore, the presence of adipose tissues in the product slows down the accumulation and redistribution of the salting substances therein. As already mentioned, muscle tissues have anisotropic properties: permeability along muscle fibres is approximately 11% greater than across the fibres, which indicates that salting substances mainly move by the intercellular space of a tissue [10]. In other words, the drop coefficient of the diffusion rate is lower along the fibres than across the fibres. The drop coefficient of the diffusion rate also depends on the initial water supply of fibres, water activity and greatly affects the rate of the salting ingredients distribution within the muscle system.

The duration of salting process can be determined by the equation of A.S. Bolshakov:

$$\tau = \frac{dh^2}{D\lg\frac{c_b}{c_i}}, \quad (3)$$

where τ is the duration of salting (diffusion), days; d is the constant equal to 1.08; h is the depth of salting substances penetration into the product, m; (for homogeneous raw materials $h = H/2$, where H is the thickness of product, m); D is the diffusion coefficient, m^2/s; c_b is the substance concentration in brine, %; c_i is the substance concentration in the brine in the tissue at a depth of h, %.

Theoretically, the diffusion rate can be elevated by increasing the temperature, solution concentration, the kinetic energy of the system (usually by stirring) or by changing the structure of raw materials (loosening, destruction, defrost, electro-stimulation, enzyme treatment, etc.) [2].

Indeed: permeability depends on the temperature rise of brine – the temperature gradient causes additional mixing of salting substances towards the heat flow – thermo diffusion [1]. Furthermore, there is an empirical connection, which takes into account the temperature conditions of the salting process, for determining the time that is required for salting meat with NaCl (without applying external actions):

$$lg\mathrm{T} = 0.0515 \times (23.5 - t), \quad (4)$$

where T is the time of salting, hours; t is the salting temperature, °C.

However, with the increase in the brine temperature, the risk of unwanted microbial processes appears. Increasing the salt concentration in the brine intensifies the exchange diffusion, but the use of high concentrations of sodium chloride (14–25%) with prolonged exposure leads to denaturation and desalting of sarcoplasmic proteins that leads to the decrease in WBC (water-binding capacity) and the formation of a denser consistency in the surface layer.

During mixing, the diffusion boundary layer, which is located on the boundary of the brine-product system separation, offers the main resistance to the diffusion flux in the brine. The acceleration of the brine movement and the transition from a laminar flow to a turbulent flow lead to a decrease in the thickness of this layer and increase the speed of the salting process [6].

Effects, leading to the increase in permeability of the sarcolemma and membrane structures of muscle fibres, causes a more rapid and more even distribution of salting substances therein. Changes in the tissue permeability during the salting process are associated with the structural changes (loosening) of tissues and increased permeability of tissue membranes.

If the brine is mixed artificially due to convection, product overhauling or for other reasons, the diffusive salt transfer in the brine is displaced with the molecular (convective) transfer. With vigorous stirring, sufficient for rapid equalization of the salt concentration in the brine, the concentration that sets in is practically close to the average concentration [4]. In this case, the diffusion salt transfer in the brine will occur only within the boundary layer, the thickness of which depends on the speed of the brine movement. Various concentration gradients are established: in the boundary layer, between the boundary layer, the surface layer of the product and inside the product (Fig. 1). At the same time, the transfer of salt from the brine into the product under other identical conditions is carried out at a maximum speed, which depends on the intensity of mixing.

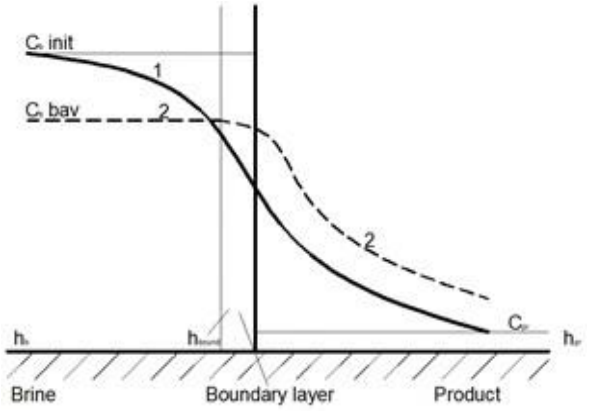

Fig. 1. Changes in the salt concentration in the brine, the boundary layer and in the product thickness: 1 – for a state of rest; 2 – stirring; $C_b init$ – initial concentration of brine; C_{pr} – product; C_{bav} – average brine concentration achieved by stirring; h_b – thickness of the brine layer; h_{bound} – thickness of the boundary layer; h_{pr} – thickness of the product layer

In practice, the boundary layer thickness may vary within wide limits. In a state of complete rest, the whole brine layer essentially acquires the properties of the boundary layer for the brine-product system. With vigorous stirring, its thickness decreases to an insignificant value [9]. Salting under the conditions of active physical (mechanical) influence – massaging, tumbling, vibration, electro-massaging – can significantly accelerate mass transfer processes, as the alternating mechanical effect, along with the diffusion exchange, causes intensive mechanical movements of the brine (and salting substances), directed to their uniform distribution through the product volume.

Lipatov S.M. solved the differential equation for the case of salt diffusion in animal tissues [1]:

$$ln\frac{C_1}{C_2} = \frac{h_2^2 - h_1^2}{4D\tau}, \quad (5)$$

where h_1 and h_2 is the distances from the body surface, between which the diffusion occurs, m; C_1 and C_2 is the concentrations at h_1 and h_2 distances from the body surface, %; τ is the maturation period in brine, days.

Provided that the diffusion process is considered on the interval between the body surface and the h depth point, i.e. if $h_1 = 0$, the equation (5) becomes:

$$ln\frac{C_1}{C_2} = \frac{h^2}{4D\tau}. \quad (6)$$

Equation (6) describes the salt concentration distribution in meat with the wet salting

The distribution process of the brine and its components in the muscle tissue under mechanical stress obeys the non-stationary filtration law and is described by the formula:

$$\frac{dp}{d\tau} = \varepsilon\frac{d^2c}{dx^2}, \quad (7)$$

where p is the pressure, Pa; τ is the duration of the process, seconds; ε is the diffusivity coefficient, m^2/s; x is the depth of brine movement, m.

The driving force of the process is produced by the pressure gradient, which occurs under the mechanical impact and an intensive filtration transfer of brine in the tissues. At the same time, the process of salting can be characterized as diffusion-filtration-osmotic.

Thus, the flow rate of salting and the intensity of salting components penetration into the product are largely dependent on the values of the diffusion coefficient D in the brine-meat system and the ε diffusivity coefficient of the tissues that most often are not known. The change in the diffusion coefficient in the salting dynamics is still poorly understood and usually limited to mathematical modelling.

Even in this case there is no uniform approach to solving the problem.

In the present study, we attempted the method of determining the diffusion coefficient of salt in beef muscle tissue empirically by creating a concentration difference in two communicating chambers, the liquids in which are separated by the studied raw material L metres thick.

The method was developed for the study on the effect of the pulsed discharges meat treatment in the brine on the permeability of muscle fibres and the penetration rate of salting components into meat, i.e., in other words, duration of the salting process.

The pulsed discharges technology for salting meat raw materials has been developed by the scientists of the department of the meat and canning technology of the North Caucasus Federal University in order to intensify the process and improve the quality and safety of meat. This technology is characterized by multifactorial physical and chemical effects on raw meat, which together were named as the electrohydraulic effect [8]. The electrohydraulic effect is accompanied by the formation of high and ultra-high hydraulic pressure, acoustic vibrations, liquid mixing intensity, the impact of powerful electromagnetic fields [11, 12].

For the formation of the electrohydraulic effect, it is necessary to form a high-pressure pulse in the transmission medium [12]. The simplest way to implement this process is to use low-inductive high-voltage energy storage devices with small capacity: high voltage provides the required amount of energy, but small inductance and capacitance of the electrical circuit – fast input of energy in the discharge gap.

The main goal of the work was to evaluate the effectiveness of the pulsed discharges technology of salting meat raw materials by determining the NaCl diffusion coefficient and the depth of salt penetration into meat samples.

OBJECTS AND METHODS OF STUDY

The object of research is the pieces of rear leg piriformis muscles (m. Piriformis) of chilled beef (+1…+2°C). The geometrical parameters of the pieces were equivalent and amounted to 50×50×100 mm. To conduct the experiment, we prepared the model brine, containing 7% NaCl solution. The main objective of the experiment was to determine the diffusion

coefficient and the depth of salt penetration into the meat in the control samples (intact or salted by the classical method) and treated samples. The pulsed discharges meat treatment was carried out in a specially designed working tank with the required strength characteristics.

To ensure purity of the experiment on determining the salt diffusion coefficient in meat, the samples were isolated from contact with the brine with a thin polyethylene film. I.e. NaCl concentration in the pieces after treatment was equal to the initial value – close to 0%. Meat isolation from contact with salt was motivated by the need to accurately calculate the concentration differences in the experiment. The control samples were intact, i.e. without any treatment.

In the course of the study on the penetration depth with the classic wet salting and pulsed discharges treatment, the test samples were exposed to the direct electrohydraulic effect deep in the brine volume, and then in parallel with the control samples had been kept in the identical brine for 24 hours.

The pulsed discharges treatment took place at a given voltage of the electric current (10 kW) and capacitance of condenser batteries (100 μF), i.e., the energy released by condensers in the established mode equalled to:

$$W = \frac{c\,u^2}{2} = 5\ kJ. \qquad (8)$$

In both cases, for determining the diffusion coefficient and for the study on the penetration depth of salting substances, a different quota of electrical pulses was applied to the test samples: 100, 200 and 300.

The method of determining the diffusion coefficient

The diffusion coefficient was determined by creating the sodium chloride concentration difference in two equivalent communicating tanks, using the studied muscle tissue as a porous membrane, through which the salt ions are migrating isothermally towards the lower concentration. The method was developed in the course of joint research by the staff of the Department of the meat and canning technology of the North Caucasus Federal University (Stavropol, Russia) and the Institute of meat technology and quality "Max Rubner-Institute" (city of Kulmbach, Germany) within the framework of the Development programme of the North Caucasus Federal University.

To carry out the studies aimed at determining the diffusion coefficient, we constructed a prototype of the laboratory setup shown in Fig. 2.

The samples of muscle tissue (2) were the sections of the control and test pieces of raw meat across the fibres with 5 mm step so that the linear dimensions of 5 × 50 × 50 mm were obtained. Then these sections were fixed between the walls of the tanks A and B via bolting (3.4) so as to completely close the opening, 20 mm in diameter. I.e. the active area of salt diffusion into muscle tissue amounted to 314 mm^2. Sequentially, after the muscle tissue was fixed, the tanks A and B were simultaneously filled with 7% NaCl solution and distilled water, respectively. The height of the liquid was adjusted to the same level to exclude an additional variable from the calculations of a pressure gradient. The risk of another variable – temperature gradient, was minimized by conducting the research in the areas with a constant temperature close to the temperature of standard physical conditions. Liquids were also kept at a room temperature until a constant temperature was reached.

Electromagnetic stirrers (6) rotationally drive magnetic beads (5) for artificial stirring and maintaining the turbulent flow in liquids. Stirring of the solution promotes continuous alignment of salt concentration, minimizing natural diffusion in the liquids and greatly reducing the diffusion salt transfer within the boundary layer, the thickness of which also depends on the rate of solution flow. Decrease in the salt diffusion factor in the boundary layer and in the solution allows determining the diffusion coefficient of the salt in the muscle tissue more accurately.

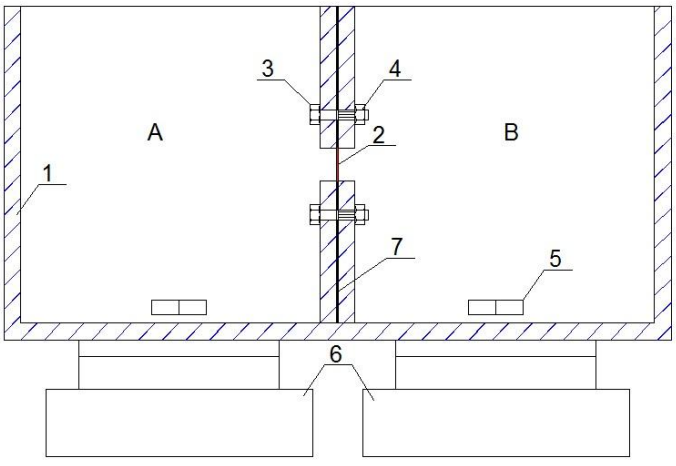

Fig. 2. A schematic view of the setup for determining the diffusion coefficient: A and B are the equivalent communicating tanks with the C_1 and C_2 salt solution concentrations; 1 – body of the device; 2 – sample of muscle tissue; 3 – stainless steel bolt; 4 – hexagonal nut made of stainless steel; 5 – magnetic beads; 6 – electromagnetic stirrers; 7 – rubber gasket between the walls.

The method of determining the depth of salt penetration

After overnight maturation in the brine, the control and test samples of raw meat were rinsed with tap water from residual salts on the surface, and then were divided into conditionally outer, middle and inner layers, 10 mm thick (Fig. 3). I.e. with the initial piece sizes 50 × 50 × 100 mm after the separation of the outer layer, the geometric parameters changed to 30 × 30× 80 mm, and the size of the inner layer made up 10 × 10 × 60 mm.

If we assume that the piece thickness is *H*, then the maximum depth of salt penetration is at a distance of $h = H/2$ – in the central plane of the inner layer.

The study on salt content was carried out using two conventional methods of Mohr and Folgard.

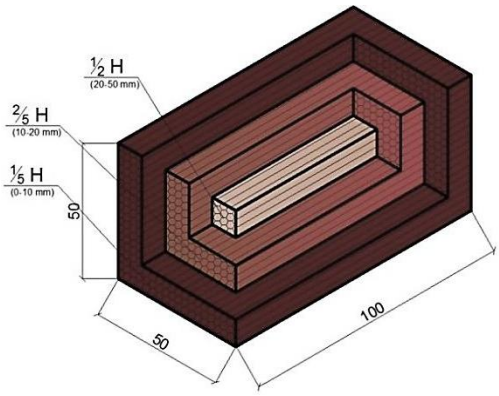

Fig. 3. Stereo metric interpretation of conditionally external, middle and inner layers of the studied pieces of meat**.**

RESULTS AND DISCUSSION

Since the determination of the diffusion coefficient of salt in the meat samples of muscle tissue had the shape of a plate with the area many times larger than the thickness, the mathematical description of the test process comes down to the solution of a one-dimensional non-stationary diffusion equation (1) with the following initial and boundary conditions: $C\ (x,\ 0) = 0$, i.e. at the beginning of the process, the muscle tissue contained no diffusible substance – NaCl.

$$V\frac{\partial C(x,0)}{\partial \tau} = -DS\frac{\partial C(x,0)}{\partial x}, \qquad (9)$$

where V is the volume of muscle tissue, through which the diffusion occurs, m^3; S is the active area of the muscle tissue, m^2; D is the diffusion coefficient.

The boundary condition shows that the intensity of salt concentration changes on the surface of the muscle tissue sample with the volume V causes the mass flow of NaCl into the thickness of the sample, the passage of which diffuses into the solution with a lower concentration [13].

$$\frac{C_{2n}-C_2}{C_1-C_2} = 1 + \sum_{n=0}^{\infty}\frac{2(a_n^2+b^2)}{a_n^2+b^2+b}\times\frac{\sin a_n}{a_n}\exp\left(\frac{Da_n^2\tau}{L^2}\right), \qquad (10)$$

where C_1 is the initial concentration in the tank A, 7%; C_2 is the initial concentration in the tank B, 0%; C_{2n} is the concentration in the tank B, % at the moment of τ, sec; $b = LS/V_2$, where L is the sample thickness, m; S is the the active area of diffusion, m^2; V_2 is the the volume of the tank B, m^3 at the moment of τ, sec; a is the nonzero positive root of the equation $a \times tga = b$.

The value C_{2n} was determined after 1, 2, 3, 4 and 24 hours after the start of diffusion. The study was conducted in triplicate for each sample, the average value of the obtained results was assigned to C_{2n}, except for the data which differed by more than 5%. The results of determining the salt content in the solution samples are given in Table 1.

Note that with each sampling, the volume of solution was reduced by 10 ml or 10^{-5} m^3. Thus, when calculating the b value, the V_2 parameter is of variable character, with the constant values $L = 0.05$ m and $S = 3.14\times10^{-4}$ m^2. In this case, the generalized formula becomes as follows:

$$b_n = \frac{LS}{V_2 - n*10^{-5}}, \qquad (11)$$

with the initial value $V_2 = 0.022$ m^3 the formula (11) comes down to the expression:

$$b_n = \frac{1.57\times10^{-5}}{0.022 - n\times10^{-5}}. \qquad (12)$$

The value of a, given that it is a nonzero positive root of the equation $a \times tga = b$, is determined graphically by the projection of the intersection point of the functions $f(a) = tga$ and $f(a) = b/a$ on the abscissa (Fig. 4).

Table 1. NaCl content in the solution of the tank B at the moment of τ, h

No. percentage point	The moment after the start of diffusion, h	Salt content in the sample, %			
		Control	Test		
			100 pulses	200 pulses	300 pulses
1	1	0.28	0.32	0.41	0.54
2	2	0.91	0.88	1.37	1.63
3	3	1.46	1.59	1.91	2.14
4	4	1.82	2.20	2.23	2.69
5	24	2.41	2.65	2.78	2.91

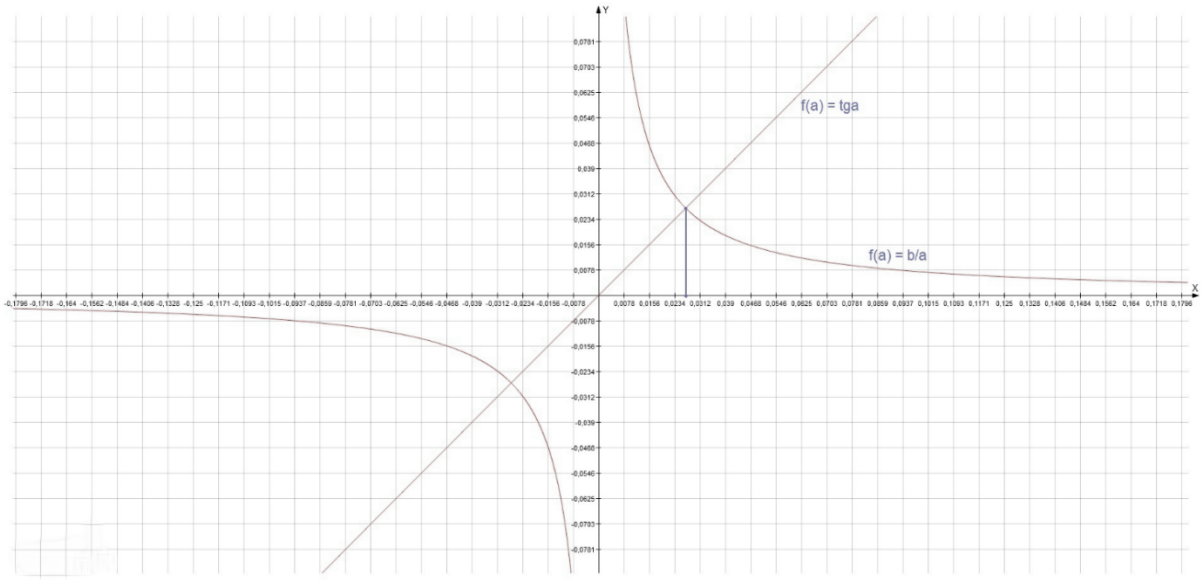

Fig. 4. Determination of the intersection point of the functions *f*(*a*) = *tga* and *f*(*a*) = *b/a* in the I coordinate quarter.

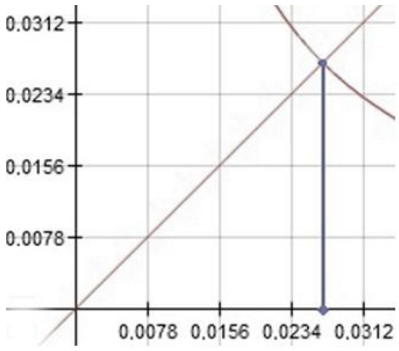

Fig. 5. Determining the value of *a* graphically.

The value of *a* with fairly close values of the dimensionless *b* parameter also varied within the narrow limits of the 0.026–0.028 range. 0.27 was taken for the average value (Fig. 5).

For all known parameters, the diffusion coefficient at the moment of τ (D_n) is determined by the formula (10):

$$\frac{Da_n^2\tau}{L^2} = \ln\frac{1+\frac{C_{2n}-C_2}{C_1-C_2}}{\frac{2(a_n^2+b^2)}{a_n^2+b^2+b}*\frac{\sin a_n}{a_n}}, \qquad (13)$$

$$D = \frac{L^2}{a_n^2\tau}\ \ln\frac{1+\frac{C_{2n}-C_2}{C_1-C_2}}{\frac{2(a_n^2+b^2)}{a_n^2+b^2+b}*\frac{\sin a_n}{a_n}}. \qquad (14)$$

The dependence of the diffusion coefficient from the process duration within the conducted experiment is given in Table 2. The studies were conducted in triplicate; deviations of more than 5% were not taken into account.

During the analysis of the data given in the table, we observed an expected tendency to the diffusion coefficient increase in the meat pieces, treated with electrohydraulic pulses. Moreover, the number of reported pulses is directly proportional to the value of the parameter under study. Thus, after the first hour, with meat pieces being treated with 100 pulses, D_1 almost equals to the diffusion coefficient in the control sample, but with a two hour interval there is difference of 0.4 mm^2/s. According to the obtained data, the diffusion of salt into the muscle tissue occurred the most effectively in the samples, treated with 300 impulses. In this case, already after 1, the diffusion coefficient of the test sample exceeded the one of the control sample by 1 mm^2/s. After 2 hours, the difference in *D* values amounted to more than 1.5 mm^2/s, after which it started to decrease slowly, which is due to the decrease in the concentration gradient. After 24 hours, the average value of the diffusion coefficient in the test samples was higher than in the control samples: by 0.03 mm^2/s if treated with 100 impulses, by 0.7 mm^2/s – with 200 impulses and by 0.13 mm^2/s – with 300 impulses.

Table 2. Results of the study for determining the diffusion coefficient of salt in the muscle tissue

No. percentage point	The studied sample	The value of the diffusion coefficient at the moment of τ, m^2/sec				
		D_1 (3 600 sec)	D_2 (7 200 sec)	D_3 (10 800 sec)	D_4 (14 400 sec)	D_{24} (86 400 sec)
1	Control	2.87×10^{-5}	1.49×10^{-5}	1.01×10^{-5}	8.37×10^{-6}	1.46×10^{-6}
2	Experimental (100 pulses)	2.88×10^{-5}	1.53×10^{-5}	1.09×10^{-5}	8.64×10^{-6}	1.49×10^{-6}
3	Experimental (200 pulses)	2.93×10^{-5}	1.61×10^{-5}	1.12×10^{-5}	8.66×10^{-6}	1.53×10^{-6}
4	Experimental (300 pulses)	2.97×10^{-5}	1.65×10^{-5}	1.15×10^{-5}	8.96×10^{-6}	1.59×10^{-6}

According to (1), with the diffusion along muscle fibres, the average penetration rate of salt into muscle tissues with the regular salting amounts to around 0.59 mm/h, with the diffusion across fibres – around 0.39 mm/h. With similar rates of the salt migration deep into muscle tissues, the changes in the diffusion coefficient by 0.15–1.5 mm^2/s will have a significant effect, as the salting rate increases proportionally to the diffusion coefficient.

It is known, that sodium chloride used for salting increases oxidation of the heme pigment of myoglobin. Oxidation of the heme centres leads to the formation of met-pigments, whereby the natural colour of meat disappears relatively quickly and it acquires the brownish-grey colour with different hues, and the more salt penetrates into the muscle tissue, the lighter the colour becomes. Fig. 6 clearly shows the trace of NaCl penetration into the muscle tissue samples.

The diameter of the grey circumference corresponded to the diameter of the opening between the walls of the A and B tanks, i.e. the trace from salt penetration equalled the cross section of the diffusion flux that proves the validity of the decision to use the one-dimensional equation of Fick, despite the anisotropic properties of muscle tissues. The area of muscle tissue, saturated with met-pigments, equalled to 3.14 cm^2. This fact confirms that made calculations are correct, with the active area of diffusion taken for 3.14×10^{-4} m^2.

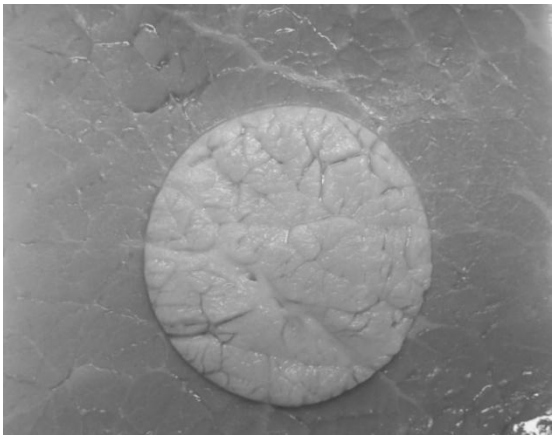

Fig. 6. The active area of NaCl diffusion deep into muscle tissue.

Thus, the use of the pulsed discharges treatment of meat pieces during wet salting resulted in a significant increase of the diffusion coefficient, which directly affects the penetration rate of salting substances into deeper muscle tissues. To obtain the empirical dependence of the salting rate from the value of effective diffusion coefficient, we conducted the study on the sodium chloride concentration at different depths of the control and test pieces after 24 hours maturation in brine. The research results are summarized in Table 3.

Electrohydraulic effect, occurring during the pulsed discharges treatment, has intense physical effect on muscle tissues. The effect causes muscle fibres to swell, increases the number of transverse slit-like ruptures, destruction of membrane structures and loosening of muscle tissues in general. Subsequent maturation of pieces in the brine causes muscle fibres to swell across the meat thickness. This salt fills transverse slit-like ruptures and actively penetrates the fibres through the ruptures in myofibrillar membranes. The salt content in test samples at a depth of 1, 2 and 3 cm was higher than in the control ones, which indicated the intensification of the sodium chloride penetration deep into meat and increase in the salting rate of meat.

Referring to the equation (6), which shows the distribution character of salt deep in the muscle tissue, the diffusion coefficient is as follows:

$$D = \frac{h^2}{4\tau \times ln\frac{C_1}{C_2}}, \quad (15)$$

Having calculated the diffusion coefficient of salt deep into meat pieces, we will obtain the values:
D of the control sample = 1.8×10^{-5} m^2/s;
D of the test sample (100 pulses) = 2.08×10^{-5} m^2/s;
D of the test sample (200 pulses) = 2.228×10^{-5} m^2/s;
D of the test sample (300 pulses) = 2.75×10^{-5} m^2/s.

The obtained values of the diffusion coefficient of salt in the control and test samples correlate with the values obtained in the experiment aimed at determining the D coefficient. The use of the pulsed discharges treatment in the wet salting technology for raw meat contributes to faster penetration and distribution of sodium chloride in the thickness of muscle tissue, i.e. intensification of the technological process.

Table 3. Sodium chloride content at different depths of the control and test samples

No. percentage point	Depth, mm	Salt content in the sample, %			
		Control	Test		
			100 pulses	200 pulses	300 pulses
1	0–10	1.80 ± 0.10	2.10 ± 0.12	2.30 ± 0.11	2.80 ± 0.13
2	10–20	1.40 ± 0.06	1.50 ± 0.09	1.60 ± 0.15	2.10 ± 0.08
3	20–30	0.90 ± 0.04	1.20 ± 0.11	1.30 ± 0.12	1.50 ± 0.12

REFERENCES

1. Kulikova V.V., Postnikov S.I. and Oboturova N.P. *Physicochemical and biochemical basis for the production of meat and meat products*. Stavropol: News Bureau Publ., 2011. 260 p. (In Russian).

2. Bratsihin A.A. *Scientific and practical aspects of the technological processes intensification with the use of nano-activated liquid media in the production of meat products*. Dr. eng. sci. thesis. Stavropol, 2009. 511 p. (In Russian).
3. Postnikov S.I. *Technology of meat and meat products. Course of lectures*. Stavropol, 2007. 112 p. (In Russian).
4. Miroshnikov E.P., Bogatov O.V. and Stadnikov S.V. *Physicochemical and biochemical basis for the production of meat and meat products.* Orenburg: GOU OG Publ., 2005. 248 p. (In Russian).
5. Filipović V., Ćurčić B.Lj., Nićetin M.R., Plavšić D.V., Koprivica G.B. and Mišljenović N.M. Mass transfer and microbiological profile of pork meat dehydrated in two different osmotic solutions. *Hemijska Industrija*, 2012, vol. 66, no. 5, pp. 743–748.
6. Dunayev S.A. and Popov A.A. *Methods for the intensification of technological processes in the meat industry: lecture notes*. Kemerovo: KemIFST Publ., 2006. 64 p. (In Russian).
7. Promtov M.A. *Machines and devices with the pulse energy impact on the substances to be treated: a textbook*. Moscow: Mechanical Engineering Publ., 2004. 136 p. (In Russian).
8. Yutkin L.A. *Electro-hydraulic effect and its application in industries*. Leningrad: Mechanical Engineering Publ., 1986. 208 p. (In Russian).
9. Jensen W.K., Devine C. and Dikeman M. (Eds.). *Encyclopedia of meat sciences, three-volume set*. New York: Elsevier, 2004. 1553 p.
10. Perkel T.P. *Physico-chemical and biochemical basis of the production of meat and meat products.* Kemerovo: KemIFST Publ., 2004. 100 p. (In Russian).
11. Oboturova N.P., Kozhevnikova O.N., Barybina L.I. and Nagdaljan A.A. Discharge-pulse effect for intensifying meat salting. *Meat Industry*, 2012, no. 12, pp. 32–35.
12. Nagdaljan A.A. and Oboturova N.P. Influence of electrohydraulic effect on the biopolymers hydration. *Current Problems of the Humanities and the Natural Sciences*, 2012, no. 12, pp. 74–78. (In Russian).
14. Djelveh G. and Gros J.B. Measurement of effective diffusivities of ionic and non-ionic solutes through beef and pork muscles using a diffusion cell. *Meat Science*, 1988, vol. 24, no. 1, pp. 11–20.
13. Bolumar T., Enneking M., Toepfl S. and Heinz V. New developments in shockwave technology intended for meat tenderization: opportunities and challenges. A review. *Meat Science*, 2013, vol. 95, no. 4, pp. 931–939.
15. Graiver N., Pinotti A., Califano A. and Zaritzky N. Diffusion of sodium chloride in pork tissue. *Journal of Food Engineering*, 2006, vol. 77, no. 4, pp. 910–918.

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