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DETERMINIG THE PARAMETERS OF THE ACOUSTIC SYSTEM FOR THE PRIMARY TREATMENT OF WOOL

L. Mikhailova
PhD, Senior Lecturer*
O. Kozak
PhD, Senior Lecturer*
N. Kosulina
Doctor of Technical Sciences,
Professor, Head of Department**
E-mail: kosnatgen@ukr.net
P. Potapsky
PhD, Senior Lecturer*
A. Cherenkov
Doctor of Technical Sciences, Professor**
E-mail: aleksander.cherenkov@gmail.com
*Department of Power Engineering and Electrical
Engineering Systems in Agroindustrial Complex
State Agrarian and Engineering
University in Podilya
Shevchenka str., 13,
Kamianets-Podilskyi, Ukraine, 32300
**Department of Technotrance and
Theoretical Electrical Engineering
Kharkiv Petro Vasylenko National Technical
University of Agriculture
Alchevskih str., 44, Kharkiv, Ukraine, 61012

Досліджено процес первинної обробки вовни з метою видалення з неї ґрунтових і гнойових забруднень, рослинних домішок і жиропоту. Первинна обробка вовни виконує ключову роль в збереженні природних властивостей вовняного волокна і дозволяє отримувати якісну сировину для текстильної промисловості. У процесі досліджень було встановлено, що для інтенсифікації процесів первинної обробки вовни необхідно використовувати акустичні коливання. Акустичні коливання діють на систему вовна-мийний розчин. Система вовна-мийний розчин знаходиться між решіточними транспортерами. Транспортери утворюють решітку з металевих стрижнів. Для визначення параметрів акустичної системи для первинної обробки вовни був проведений аналіз трьох задач. Задачі були пов'язані: з розсіюванням акустичних коливань на металевій решітці, на шарі вовна-мийний розчин і об'єднання рішень двох задач в одне за допомогою методу матриць розсіювання. Проведені дослідження дозволили визначити параметри системи для первинної обробки вовни акустичними коливаннями, що дозволяє досягти більшої ефективності в очищенні вовни в порівнянні з існуючими аналогами. В результаті теоретичних і експериментальних досліджень було встановлено, що промивка вовни повинна здійснюватися при наступних параметрах акустичних коливань в миючому розчині: частота звукового поля 1,1±0,1 кГц; інтенсивність звуку 1,1±0,01 Вт/см². При цьому товщина шару вовни на транспортері 0,06±0,01 м; швидкість руху транспортера 0,1 м/с; кількість перетворювачів на ванну 8±1 штук.

Застосування оптимальних параметрів в процесі безперервної промивки шерстяного волокна в водному розчині дозволяє отримати залишок жиру на шерсті в межах 1,5 % від кількості жиру немитої вовни при ГОСТ України до 2 %

Ключові слова: первинна обробка вовни, параметри акустичних коливань, коефіцієнт відбиття акустичної хвилі

1. Introduction

The main type of wool used in the woolen industry is sheep wool. It is used to produce a wide range of wool products for consumer and industrial purposes. The quality and cost of products made from wool mainly depend on the primary treatment of wool [1]. An analysis of the technological process and equipment used at factories during primary treatment of wool revealed their significant drawbacks: negative impact on the environment, energy-intensive production, materials consumption, large dimensions and mass, low quality of fibers [2]. Given this, there is a need to develop the

new technology and equipment for the primary treatment of wool based on the use of acoustic oscillations.

Applying acoustic oscillations for washing wool would make it possible to utilize neutral and slightly alkaline solutions, to reduce consumption of detergents and wastewater. Acoustic technology allows maintaining the technological properties of wool fibers, conducting the disinfection of wool and cleaning solutions. The process of wool washing based on acoustic oscillations would make it possible to automate the waste-free process and exclude flammable and toxic solvents from the production cycle [3].

2. Literature review and problem statement

Paper [4] reports analysis of wool-washing machines with continuous technological process. Two principles in the structural design of washing machines were established: bath-washing and fiber-transporting. The first principle requires that module of the bath should be maintained, as well as a certain level of liquid be kept in bowls; the second principle, depending on the technological scheme, shall not be subject to compliance with these conditions.

The Belgian machine Etoile employed rake bowls with intermediate pressing shafts for washing wool [5]. The disadvantage of this design is the difficulty of repair work, as well as big losses of fibers due to intensive mechanical influence.

To wash fibrous materials, a device was proposed that uses electric discharges in the washing liquid. Electrodes were installed in the washing medium of the bowl and were electrically connected to a current pulse generator [6]. The shortcomings of this device are the destruction of wool fibers under the influence of spark discharges. This results in lowering their tensile strength and intense destruction of equipment surface under the influence of cavitation and electrochemical processes.

To intensify soaking in a regular washing bowl, a "device for the continuous steeping of fibrous material with a washing liquid" was developed and patented [7]. The idea behind the patent was to create turbulence in the liquid in a displaced layer of wool using nozzles installed in the sidewalls of the bowl. The disadvantage of steeping wool before washing is the removal of a large amount of fat at steeping, especially the cross-bred wool, as well as an increase in the volume of wastewater.

Study on wool-washing with a flow of water [8] showed that the disadvantage of a given technology is the improper washing of wool. After washing, wool contains significant amounts of soil and manure contamination. In the flat-layered washing machine wool moved in a fixed position between two perforated clamped series of wedges, immersed in the cleaning solution [9]. The solution, as a viscous fluid, displaces when a belt moves towards the side of the wedge and is forced through a layer of wool with belts in the transverse direction. Depending on the inclination angle of the upper and lower wedges, a solution passes through a layer of wool (when belts move) upwards or downwards. The shortcoming in the operation of this machine is the unsatisfactory washing of wool, containing a significant amount of soil and manure contaminants (sand remains in wool as well).

When washing wool in aqueous solutions at these units, the consumption of water and reagents per 1 ton of washed wool was 12...25 m^3 of water in the absence of water treat-

ment plants, and 35...45 m^3 of water in their presence. To wash wool, it is required to add to a washing solution 14 kg of soda, 25 kg of soap (60 % of fatty acids), the fine wool requires 36 kg of soap and 80 kg of soda.

Designs of machines, based on the fiber-transporting principle, using the irrigation of a wool layer through nozzles under pressure, were first proposed in Australia [10]. Studies have shown that the process of wool washing by using the nozzles had such advantages as: it is continuous and is cheaper than the standard process; wool washed this way is better at wool combing; pH of the washed wool does not exceed 8, despite the use of alkali.

However, along with the advantages, these machines have a number of disadvantages: there are several places in a machine where the intense entanglement of fibers occurs. The temperature of washing solution must be kept high, at least 65 °C (typically about 80 °C), causing great losses of heat and steam condensation. Due to the high rates of fluid the fine sand is not settled and, together with wool, comes to wool combing. Wool after jet washing contains 6 times more soil contaminants than after a standard washing.

The Japanese firm Futaba produced washing machines with nozzles, consisting of four or five bowls. Each bowl had two nozzles installed at the top and bottom. Liquid from each nozzle was discharged in the form of irrigation screen onto a layer of wool, clamped between two moving conveyors. Every bowl had its working pump and the tank. Such a machine had the same disadvantages as machines from Australia [11].

Paper [12] described the use of acoustic oscillations of audible and US frequencies in the fur industry. Acoustic fields were applied in tanning, dyeing, and degreasing of fur skins of animals. One of the main processes in the fur industry is the process of degreasing and removing impurities from the hair pelts (sheepskin, etc.). The application of US oscillations makes it possible to intensify the process of skin washing, it also prevents reverse subsidence of washed contaminants on skin. The best results were obtained when applying hydrodynamic emitters with a frequency of 5...10 kHz, washing time in this case reduces by almost 20 times.

Acoustic oscillations are used extensively for cleaning textile fabrics [13]. Because the impedance of a washing solution and a textile fabric are significantly different, the transfer of sound energy from the solution into fabric is accompanied by significant losses for reflection and absorption. Larger losses occur when switching from one layer of a fabric to another. For example, at frequency 22 kHz, one can simultaneously wash four layers of a cotton cloth, at 30 kHz – three, at 46 kHz – two, and at 450...800 kHz – one.

Paper [14] describes the use of ultrasound for wool coloring. The fur coloring process was conducted at a frequency of ultrasound of 1.2 kHz and an intensity of 0.8 W/cm^2. The application of ultrasound made it possible to obtain a uniform and stable coloration of wool.

Ultrasonic oscillation with a frequency of 1.8 kHz were used for a low temperature dyeing of wool with acidic paints [15]. The application of ultrasonic oscillations with the intensity of 1.3 W/cm^2 reduced the duration and improved the quality of wool coloring.

Thus, an analysis of the scientific literature revealed that the main advantages of wool washing by means of acoustic oscillations compared to traditional methods are the improvement of quality, whiteness, and softness of wool fibers. Advantages of acoustic technology include a decrease in the time

required for washing wool, the reduced consumption of detergents. Acoustic wool washing can be conducted at relatively low temperatures (40...50 °C), with a possibility to automate wool treatment. A significant reduction in water consumption could be due to its multiple usage in a closed cycle. The acoustic system of wool treatment implies the disinfection of wastewater and wool without applying toxic chemicals.

However, creating an acoustic technology and systems for the primary treatment of wool requires theoretical studies into interaction between acoustic waves and a layer of wool, shielded by metal gratings. The research must be undertaken on determining the parameters of acoustic oscillations, as well as parameters for a device for the continuous washing of wool using hydrodynamic converters.

3. The aim and objectives of the study

The aim of this study is to create a technology and a device for wool washing based on acoustic fields.

To accomplish the aim, the following tasks have been set:
– to solve a problem on the interaction between acoustic waves and a layer of wool, shielded by metal gratings;
– based on the experimental studies, to define the parameters of acoustic oscillations and for a device for wool washing.

4. Theoretical analysis of the process of primary treatment of wool by acoustic oscillations

The intensity of wool washing depends on the intensity of acoustic oscillations, velocity of the washing solution jet at the outlet from hydrodynamic emitters, motion speed of mesh belts of conveyors, and the degree of compression of the layer of wool by guiding rollers. The proposed design makes it possible to widely modify the modes of washing, depending on wool contamination and requirements to its quality after washing.

Consider a model that makes it possible to determine the optimum parameters for the proposed device. We chose as the model of wool a solid medium that fills the layer of thickness h with the following parameters: ρ_1 is the density of the medium; c_1 is the speed of sound propagation; η_1 is a viscosity coefficient. This layer of the medium is in a liquid with a density of ρ_1, sound speed c_2 and a viscosity coefficient η_2. We shall introduce a Cartesian coordinate system so that the layer of wool can be assigned by inequality: $-h \leq z \leq 0$.

In planes $z=0$ and $z=-h$, there are metal periodic gratings, formed from rods with a circular cross-sectional shape (Fig. 1).
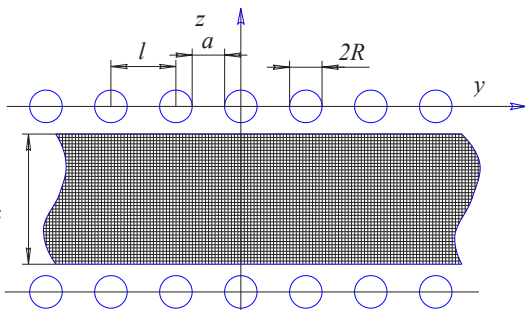

Fig. 1. Cross-section of a layer of wool and shielding gratings

The axis of rods is parallel to the OX axis, periods equal to l are located along the OY axis, rods' radius is R, and the distance between them is a. Wool is between these gratings. Let the origin of the introduced Cartesian coordinate system be located along the axis of one of the rods from the upper grating.

We shall assume that the gratings are endless along the OX and OY axes. Next, suppose that the exciting acoustic wave propagates in the negative direction of the OX axis perpendicular to the plane of the grating. Frequency f of the exciting acoustic wave and a period of the gratings satisfy inequality $lf/c_2 \ll 1$. In this case, the basic magnitude that characterizes the interaction between an acoustic wave and gratings and a layer of wool are the coefficients of reflection and passage, normalized for the amplitude of the exciting wave.

To determine these coefficients, it is required to solve a boundary problem that describes the process of interaction between an acoustic wave and the gratings, located at the borders of the layer of wool and the wool itself.

Let U_1 and U_2 be the potential functions of media that simulate wool and liquid, respectively, in which the exciting acoustic wave propagates. Then, according to [16], these functions must satisfy the equations of linear acoustics:

$$\frac{\partial^2 U_1}{\partial t^2} + \gamma_1 \frac{\partial U_1}{\partial t} - c_1^{-2} \Delta U_1 = 0, \quad -h < z < 0, \tag{1}$$

$$\frac{\partial^2 U_2}{\partial t^2} + \gamma_2 \frac{\partial U_2}{\partial t} - c_2^{-2} \Delta U_2 = 0, \quad z > 0, \quad z < -h, \tag{2}$$

where at a harmonic time dependence with frequency ω

$$\gamma_1 = \frac{4\omega^2 \eta_1}{3 c_1^2 \rho_1^2} \text{ and } \gamma_2 = \frac{4\omega^2 \eta_2}{3 c_2^2 \rho_2^2}$$

are the attenuation coefficients in a layer of wool and liquid.

Potential functions are associated with speed and pressure through the following relations [16]:

$$\vec{V}_1 = \frac{1}{\rho_1} \mathrm{grad}\, U_1, \quad P_1 = \frac{\partial U_1}{\partial t} - \gamma_1 U_1,$$

$$\vec{V}_2 = \frac{1}{\rho_2} \mathrm{grad}\, U_2, \quad P_2 = \frac{\partial U_2}{\partial t} - \gamma_2 U_2.$$

The boundary conditions of perfect rigidity must be satisfied at the gratings surfaces, specifically, a speed component, normal to the grating, should tend to zero. The conditions for conjugation are assigned at the media interface – an equality of pressures and speed components, normal to the boundary, from fluid and a layer of wool.

Potential function of a flat exciting acoustic wave takes the form:

$$U^i = A e^{-jk_2 z - j\omega t}, \tag{3}$$

where A is the wave amplitude,

$$k_2 = \frac{\sqrt{\omega(\omega + j\gamma_2)}}{c_2}.$$

In a general case, the stated problem is three-dimensional. However, given the above conditions, it is possible as a

first approximation to reduce it to a two-dimensional one in the *YOZ* plane (Fig. 1).

As a result of diffraction of the acoustic wave, there emerge the reflected and passed waves at the upper grating. Let us denote their potential function as U^s. Complete field $U=U^i+U^s$ should satisfy at the boundaries of the perfectly rigid rods of the grating the following boundary condition:

$$\frac{\partial U}{\partial \vec{n}}\bigg|_{L_p} = 0, \quad p = 0, \pm 1, \pm 2, \ldots,$$

where L_p is the cross-sectional contour of the p-th rod; $\vec{n}$ is the normal to contour L_p.

Solution to the wave equation for potential function U in conjunction with the boundary condition is derived in the form of a superposition of the simple layer potentials, distributed among all rods of the grating [17].

Because the diffusing grating is periodic with a period of l, then the acoustic wave diffracted on it takes the form:

$$U^s(y,z) = \begin{cases} \sum\limits_{p=-\infty}^{+\infty} R_p\, e^{j\frac{2\pi}{\ell}py}\, e^{j\sqrt{k_2^2-\left(\frac{2\pi}{l}p\right)^2}\,z}, & z > R, \\ \sum\limits_{p=-\infty}^{+\infty} T_p\, e^{j\frac{2\pi}{\ell}py}\, e^{-j\sqrt{k_2^2-\left(\frac{2\pi}{l}p\right)^2}\,z}, & z < -R, \end{cases} \quad (4)$$

where

$$R_p = \frac{j\pi}{l\sqrt{k_2^2-\left(\frac{2\pi}{l}p\right)^2}} \times$$

$$\times \int\limits_{L_0} f(y_0,z_0)\, e^{j\sqrt{k_2^2-\left(\frac{2\pi}{l}p\right)^2}\,z_0}\, e^{-j\frac{2\pi}{l}p\,y_0}\, ds; \quad (5)$$

$$T_p = \delta_p^0 + \frac{j\pi}{l\sqrt{k_2^2-\left(\frac{2\pi}{l}p\right)^2}} \times$$

$$\times \int\limits_{L_0} f(y_0,z_0)\, e^{-j\sqrt{k_2^2-\left(\frac{2\pi}{l}p\right)^2}\,z_0}\, e^{-j\frac{2\pi}{l}p\,y_0}\, ds; \quad (6)$$

are the scattering coefficients in the positive and negative directions along the *OX* axis, respectively.

Here ds is the element of the rod's cross-sectional arc, δ_p^0 is the Kronecker symbol, p is the number of one of the selected rods, index 0 denotes coordinates of the selected rod, $f(y_0,z_0)$ is the simple layer potential [17], which satisfies the integral equation by Fredholm of second kind. It follows from (4) that the potential function $U^s(y,z)$ takes the form of a superposition of flat waves.

By solving the Fredholm equations, and using the asymptotic formulae for cylindrical functions at small values of arguments, we derived the following expressions for the coefficients of reflection and passage of the acoustic wave, arriving onto the grating:

$$R_{1ref.} = -jQ\left[\frac{1}{1+jQ} + \frac{2}{(1-jQ)^2}\left(1+\frac{\pi^2 R^2}{3l^2}\right)\right], \quad (7)$$

$$T_1 = 1 - jQ\left[\frac{1}{1+jQ} - \frac{2}{(1-jQ)^2}\left(1+\frac{\pi^2 R^2}{3l^2}\right)\right], \quad (8)$$

where

$$Q = \pi^2\left(\frac{k_2 R}{2\pi}\right)^2.$$

Let us now consider the scattering of an acoustic wave on a layer of wool placed in a liquid, and that has the above-mentioned parameters. Let us assume that in this case the *XOY* plane coincides with the top layer of wool.

Since the potential function of an exciting acoustic wave (3) does not depend on spatial variables x and y, and a layer of wool is homogeneous along the *OX* and *OY* axes, potential functions U_1 and U_2 will also not depend on these variables.

Solving wave equations (1) and (2) taking into consideration the conditions for conjugation at the fluid–wool interface leads to the following coefficients of reflection and passage of an acoustic wave:

$$R_{ref.} = \frac{A_+ A_-\left(e^{-j2k_1h}-1\right)}{A_-^2-A_+^2\, e^{-j2k_1h}}, \quad T = \frac{e^{-jk_1h}\left(A_-^2-A_+^2\right)}{A_-^2-A_+^2\, e^{-j2k_1h}}, \quad (9)$$

where

$$A_\pm = \frac{\omega+i\gamma_2}{\omega+i\gamma_1} \pm \frac{k_2\rho_1}{k_1\rho_2}; \quad k_1 = \frac{\sqrt{\omega\left(\omega+j\gamma_1\right)}}{c_1}.$$

In this case, potential function in a layer of wool can be represented as follows:

$$U_1 = \frac{A\left(A_-^2-A_+^2\right)}{2\left(A_-^2-A_+^2\, e^{-j2k_1h}\right)}\left(A_-\, e^{jk_1z} + A_+\, e^{-jk_1z-j2k_1h}\right). \quad (10)$$

This is the solution to the original problem on the interaction between a flat acoustic wave and a layer of wool.

We presented earlier a solution to two auxiliary problems on the acoustic wave diffraction at gratings from the perfect rigid rods and a layer of wool. We obtained analytical expressions for the respective coefficients of reflection and passage (7)–(10). Using the method of scattering matrices [17] and the solution to these two auxiliary problems, we shall obtain coefficients of reflection and passage for a layer of wool, shielded by two periodic gratings from the perfectly rigid round rods.

Thus, let R_{ref}, T be the reflection and passage coefficients for a layer of wool (9) and R_{ref}, T be the reflection and passage coefficients for a periodic grating (7, 8). We denote h_1 to be the distance between the grating and the boundary of a wool layer at the top and bottom.

At known magnitudes of R_{ref}, T, R_{1ref}, T_1 and A, the scattering matrix method leads to a linear system of equations of the sixth order relative to the unknown amplitudes of the acoustic field that has passed a layer of wool, was reflected by a layer of wool, and has entered the layer of wool.

Solving a given system of linear equations has led to the following values for the coefficients of reflection $\bar{R}_{ref.}$ and passage $\bar{T}$ of the acoustic field through a layer of wool, shielded by two gratings. Neglecting the phase foray between the gratings and the boundaries of the layer of wool, we obtain:

$$\bar{R}_{ref.} = R_{1ref.} + \frac{T_1^2\left[R_{ref.} - R_{1ref.}\left(R_{ref.}^2 - T^2\right)\right]}{\left(1-R_{1ref.}\, R_{ref.}\right)^2 - T^2\, R_{1ref.}^2}, \quad (11)$$

$$\overline{T} = \frac{T\, T_1^2}{\left(1 - R_{1ref.}\, R_{ref.}\right)^2 - T^2\, R_{1ref.}^2}. \tag{12}$$

Formulae (11), (12), based on the assigned material parameters of wool with an aqueous solution and geometrical parameters of the gratings of transporters, make it possible to calculate coefficients of reflection and passage for the exciting acoustic wave.

Based on these formulae, we calculated optimal geometric parameters for gratings (rods' radius, gratings' period) at which the reflection coefficient of an acoustic sound wave reaches a minimum. The minimum of the reflection coefficient characterizes maximum energy absorption from the exciting acoustic wave in wool [18]. Fig. 2 show results of the calculations.

We examined the reflection coefficient module dependence (the ratio of the amplitude of the reflected wave to the amplitude of the exciting wave) on the magnitude R/l – the ratio of the rods' radius to the period of the grating.

It follows from the calculations performed that the minimum coefficient of the acoustic wave reflection from the wool-liquid layer, shielded by the conveyor gratings, depends on the ratio of the radius of the cross-section of gratings' rod to its period.
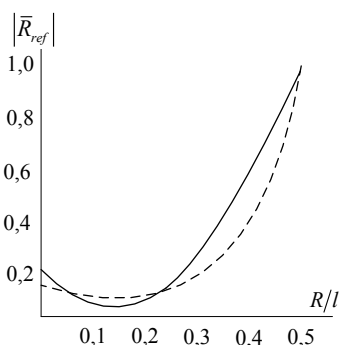

Fig. 2. Dependence of the reflection coefficient module on ratio of the radius of grating's rods to its period:
solid line – ρ_1=5 g/cm^3; dotted line – ρ_1=4 g/cm^3

Calculations were performed at the following values of parameters: f=1 kHz; γ_1=0,8; c_1=100 m/s; ρ_1=1.3 g/cm^3 are, respectively, the acoustic wave frequency, damping factor, the speed of sound, density in the fluid-wool medium; h=10 cm is the thickness of the wool layer.

Thus, in order to obtain the reflection coefficient module $|\overline{R}|<0,1$, it is required that the ratio of a rod's radius to the period of gratings should stay in the range of $R/l \approx 0,14$. In this case, an increase in the density of the wool-fluid layer contributes to that this layer increases the absorption of the sound wave power.

5. Experimental study to determine the parameters of acoustic oscillations and for a device to wash wool

We have designed an installation for experimental studies. The installation consisted of a rectangular container with a length of 1 m and a width of 0.5 m, with transparent walls for monitoring the process of wool washing; the container was filled with water to volume of 250 liters.

To feed a washing solution to flat hydrodynamic emitters, we used a horizontal electro-pump unit with the centrifugal multi-stage pump NSG 4-60 (Ukraine), with a flow rate of 4 m^3/h and a head of 60 m. The electro-pump unit was set into motion by an electric motor with a power of 1.5 kW and a rotation frequency of 2,900 rpm. The pressure, generated by the pump, was measured by the reference manometer of type MO11202 (Ukraine).

In the course of experimental study, we placed semi-thin wool with a fineness of 43 µm into a bath between grids of the conveyor belt (Turboatom, Ukraine). The thickness of the wool was 10 cm, its weight was 2 kg, and, accordingly, the bath module was 1:125. The amount of wool fat on wool fibers was 9.6 %, sweat – 7.8 %, mineral impurities – 20.1 %. The content of fat, sweat and mineral contaminants was determined at the laboratory of ZAO "Kharkiv-wool" (Ukraine) before and after the washing of wool.

Displacement of a conveyor belt was imitated by displacing the hydrodynamic emitter along the guides of the hydraulic tray, which held the washing bath.

Excitation of acoustic oscillations in the bath was induced by flat hydrodynamic emitters, which received a washing solution under a head of 30...60 mm H$_2$O.

A jet of the detergent liquid that is discharged through the opening in a flat hydrodynamic emitter carries a contamination into the volume of the container, preventing the repeated sedimentation of impurities on wool. Adjustment of the cleaning solution feed, and therefore the intensity of oscillations, was performed using the adjusting valve, installed behind the pump.

We determined parameters of the acoustic field for washing dirty wool based on full-factorial planning of the second order. Values for the factors and their variation intervals are given in Table 1.

Table 1

Values for the examined process factors

Variation interval and levels of factors	Frequency of sound oscillations, kHz	Intensity of sound oscillations, W/cm^2	Thickness of a wool layer on a conveyor belt at washing, m	Conveyor belt motion speed, m/s	Number of converters per bath, pcs.
Zero level, x_i	1.5	1.0	0.08	0.10	6
Variation interval δ_i	0.5	0.2	0.04	0.05	2
Upper level x_i=+1	2	1.2	0.12	0.15	8
Bottom level x_i=−1	1	0.8	0.04	0.05	4
Encoded designation	x_1	x_2	x_3	x_4	x_5

To implement a rotatable plan of the second order, for the number of factors $K=5$, we accept half-replica 2^{5-1} as a planning kernel [19]. The regression equation of the examined process is then determined from expression.

$$
\begin{aligned}
y = {} & b_0 + b_1 x_1 + b_2 x_2 + b_3 x_3 + b_4 x_4 + b_5 x_5 + \\
& + b_{12} x_1 x_2 + b_{13} x_1 x_3 + b_{14} x_1 x_4 + b_{15} x_1 x_5 + \\
& + b_{23} x_2 x_3 + b_{24} x_2 x_4 + b_{25} x_2 x_5 + b_{34} x_3 x_4 + \\
& + b_{35} x_3 x_5 + b_{45} x_4 x_5 + b_{11} x_1^2 + b_{22} x_2^2 + \\
& + b_{33} x_3^2 + b_{44} x_4^2 + b_{55} x_5^2,
\end{aligned}
\tag{13}
$$

where y is the output parameter; x_i are the factors that determine the progress of the process (input parameters); b_0, b_i, b_{ij}, b_{ii} are the regression coefficients to be determined.

To construct the second-order plan, we shall apply data given in Table 2 [19].

Table 2

Data for constructing a rotatable plan of the second order

Number of factors, K	Number of kernel points	Number of star points, N_α	Number of zero points, N_0	Star points, α	Number of experiments, N
5	16	10	6	2	32

When employing the standard second-order plans procedure, we constructed matrices of experiment planning, regression coefficients computation, determining the variance of adequacy and results of data processing.

Upon carrying out measurements and calculations, we derived a regression equation for the residual fat on wool after washing

$$
\begin{aligned}
y = {} & 2,3 + 1,0 x_1 + 1,5 x_2 + 1,2 x_3 + 2,2 x_4 - \\
& - 1,3 x_5 + 1,2 x_1 x_2 + 1,4 x_1 x_3 + 2,0 x_1 x_4 + \\
& + 1,3 x_1 x_5 + 1,1 x_2 x_3 + 1,2 x_2 x_4 - 1,4 x_2 x_5 + 1,0 x_3 x_4 + \\
& + 1,3 x_3 x_5 - 1,2 x_4 x_5 + 1,5 x_1^2 + 1,0 x_2^2 + 2,0 x_3^2 + 1,5 x_4^2 + 1,9 x_5^2.
\end{aligned}
\tag{14}
$$

Testing the significance of regression coefficients was performed at significance level $\alpha=0.05$ based on the Student's criterion [19]. Taking into consideration the significance of the coefficients, the regression equation for washed wool takes the form of equation (14).

Based on the test of a given equation for the adequacy of the model by the Fisher criterion [19, 20], we conclude that the equation adequately describes the actual process, and therefore makes it possible to assess the character of the impact of each factor on the response function. In addition, it became possible to practically use the derived model to predict values for the output parameter Y in the region of variation of parameters x_i. In order to find the optimal process parameters, we solved a system of equations derived by equating to zero the values of gradients of the components calculated from expression

$$
\frac{\partial y}{\partial x_i} = b_i + 2 b_{ii} x_i + \sum_{i=1}^{n} b_{ij} x_j,
\tag{15}
$$

where x_i, x_j are the encoded value of the factor from which the derivative is taken, and interacting with it, respectively; b_i, b_{ii}, b_{ij} are the regression equation coefficients.

The following system of equations was derived for expression (14):

$$
\left.
\begin{aligned}
\frac{\partial y}{\partial x_1} &= 1,0 + 1,2 x_2 + 1,4 x_3 + 2,0 x_4 + 1,3 x_5 + 2 \cdot 1,5 x_1 = 0, \\
\frac{\partial y}{\partial x_2} &= 1,5 + 1,2 x_1 + 1,1 x_3 + 1,2 x_4 - 1,4 x_5 + 2 \cdot 1,5 x_2 = 0, \\
\frac{\partial y}{\partial x_3} &= 1,2 + 1,4 x_1 + 1,1 x_2 + 1,0 x_4 + 1,3 x_5 + 2 \cdot 2 x_3 = 0, \\
\frac{\partial y}{\partial x_4} &= 2,2 + 2 x_1 + 1,2 x_2 + 1,0 x_3 - 1,0 x_5 + 2 \cdot 1,5 x_4 = 0, \\
\frac{\partial y}{\partial x_5} &= 1,9 + 1,3 x_1 + 1,4 x_2 + 1,3 x_3 - 1,3 x_4 + 2 \cdot 1,9 x_5 = 0.
\end{aligned}
\right\}
\tag{16}
$$

Solving the system of equations (16) yields the following values of factors in the optimal point:

$$
x_{1\text{opt}}=-0.8; \; x_{2\text{opt}}=0.5; \; x_{3\text{opt}}=-0.5; \; x_{4\text{opt}}=0.1; \; x_{5\text{opt}}=1.08,
$$

which corresponds to the following values of natural parameters: frequency of the sound field is 1.1 ± 0.1 kHz, sound intensity is 1.1 ± 0.01 W/cm^2, thickness of the wool on the conveyor is 0.06 ± 0.01 m, motion speed of the conveyor is 0.1 ± 0.01 m/s, the number of transducers per bath is 8 ± 1 pieces.

It was found as a result of the experiment that the washing of wool should be performed by acoustic oscillations with a frequency of 1.1 ± 0.1 kHz and a sound intensity of 1.1 ± 0.01 W/cm^2. The tests were conducted for the thickness of the wool layer on the conveyor of 0.06 ± 0.01 m and a conveyor motion speed of 0.1 ± 0.01 m/s. To treat the wool, we used 8 ± 1 pieces of acoustic transducers per bath.

The application of optimal parameters in the process of continuous washing of wool fibers in an aqueous solution makes it possible to obtain the residual fat on wool within 1.5 % of the amount of fat in the unwashed wool while GOST of Ukraine permits up to 2 % of fat [21].

To wash wool, it is necessary to use flat hydrodynamic converters of sound oscillations at a frequency of 1...2 kHz under the following parameters:
– length of rods – 25...30 cm;
– width of rods – 3...4 mm;
– thickness of rods – 1...2 mm;
– period of the converter's grating – 5...6 mm;
– number of rods – 18...20.

Such parameters make it possible to obtain the quality of washed wool with the residual fat on fibers within 1.5 %, the content of mineral impurities less than 1 %. For control, breaking load of the unwashed wool was 802.6 sN, and the relative strength – 4.68 sN/Tex. For the wool treated with acoustic oscillations, the breaking load was 796.8 sN, and the relative strength was 4.3 sN/Tex.

Influence of the acoustic field on tensile strength and the relative strength of wool was investigated using the method of infrared spectroscopy at the IR-spectrophotometer Specord M80 (Germany).

The measurements were taken in two ranges – 3,700... 2,700 cm^{-1}, where the oscillations of O–H bonds (hydroxyl groups) are observed, N–H bonds (amide groups), C–H bonds (methyl and methylene groups), and 1,700...1,200 cm^{-1}, where we registered fluctuations of C–O and C–N amide and carbonyl groups. The samples were made by shredding the wool and pressing it it into tablets with anhydrous potas-

sium bromide. The acquired spectral curves were processed using the software package "Spectral Data Lab" and normalized for the same area.

We took 4 samples of semi-fine wool for the analysis, two of which had been treated in the acoustic field, and two had been treated without the acoustic field: the latter samples were used as control. Spectrograms of the control and experimental wool are shown in Fig. 3, 4.
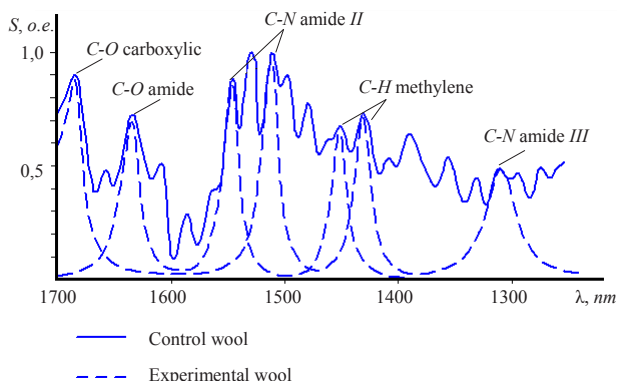

Fig. 3. Characteristic bands in the infrared spectra of the control and experimental wool

The spectral curves (Fig. 3, 4) for experimental wool we observe a marked low-frequency offset of the wide band of a hydrogen-bound hydroxyl group that can indicate the formation in wool of additional components, forming strong hydrogen bonds through the hydroxyl groups of amino acids of the protein. The experimental samples have significant absorption in the region where there are fluctuations of the CH_3, CH_2, CH groups, characteristic of the esters of fatty acids. For the experimental batch of wool, we observe in this region a significantly lower absorption; in addition, there is an intensive maximum of the free carboxyl group, which testifies to the existence of a large amount of de-esterified acid residues. The lower intensity of the band of valence fluctuations in CH_2-groups in the experimental samples, compared to control, should be attributed to the destruction of protein molecules of wool.
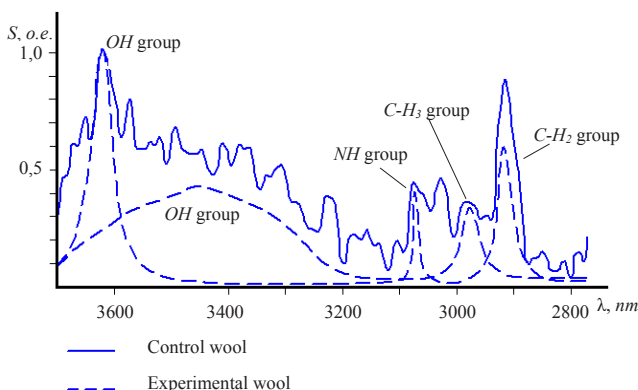

Fig. 4. Characteristic bands in the infrared spectra of the control and experimental wool

The spectrograms demonstrate a noticeable shift and a change in the band that corresponds to fluctuations of the bound hydroxyl group. This is indicative of the change in the secondary and tertiary structure of protein molecules of wool. Changes in the latter leads to the destruction of the old

and the emergence of the new hydrogen bonds, and therefore to altering the degree of binding of hydroxyl groups. The formation of new hydrogen bonds is associated with the disappearance of amide group, hence the peak in the region of 3,020 cm^{-1} must reduce its intensity in proportion to binding. Experimental studies involved semi-fine wool of class 60^k with samples of 5 g. The relative breaking load was determined at the staple dynamometer DSh-3M (Ukraine) in line with the standard. The absolute breaking load and relative tensile strength did not differ from the control sample.

6. Discussion of research results on determining the parameters of acoustic oscillations and for a device for washing wool

Application of acoustic oscillations for primary treatment of wool will make it possible to develop a new technology. Acoustic technology is different from the traditional one by the greatly reduced consumption of energy and water, by the improved quality of scoured wool. The use of acoustic oscillations for washing wool will make it possible to reduce consumption of detergents, to carry out the disinfection of wool and cleaning solutions, to accelerate the process of wool treatment, to eliminate flammable and toxic solvents. We consider it a disadvantage that the use of acoustic oscillations as an alternative to traditional methods of wool washing presents researchers and designers with a number of tasks. These include the development of devices that generate these oscillations, as well as the selection of parameters for these devices, and a technique for the passage of the treated wool through the zone of impact of acoustic oscillations.

This paper addresses the effect of acoustic field from a hydrodynamic emitter with a directional fluid flow on the layer of wool between the two belts of conveyors, which drag the wool through this sound field. The conveyors themselves are treated as periodic gratings from metal rods with a circular cross-section. Efficient washing of wool is possible in the case when energy of the acoustic wave is maximally absorbed by the layer wool-water.

Since solving a given task involves three independent problems, it became necessary to find a solution to each problem separately and then combine them into one. The problems were linked: to the scattering of acoustic oscillations on the metal grating, on the layer of wool-washing solution, and on the structure, consisting of a grating and a layer of wool with water.

Each problem was solved based on the construction of an adequate mathematical model and obtaining the resulting solution using a scattering matrix method. All the solutions were derived in a formal statement and with subsequent simplification at the expense of disregarding irrelevant parameters.

The result of the study is the derived expressions for the coefficients of reflection and passage of a sound wave through a layer of wool in a liquid, limited by the metal gratings that transport it. An analysis of formulae allowed us to propose parameters of the structure, based on the maximum absorption of the sound wave energy in wool. In order to obtain the minimum coefficient of reflection of a sound wave from a layer of wool-liquid, shielded by the conveyor's gratings, less than $\left|\overline{R}\right|_{omp} < 0{,}1$, it is necessary to use the ratio of the grating's rods radius to its period within $R/l \sim 0{,}14$. Reducing the power of a sound wave, reflected from a layer

of wool-liquid, by less than 1 % is possible for the following parameters of the grating: $R\approx0.8$ mm, $l=5.7$ mm.

It was established in the course of theoretical and experimental studies that the washing of wool should be carried out at the following parameters of acoustic oscillations in a washing solution: frequency of the sound field is 1.1±0.1 kHz; the sound intensity is 1.1±0.01 W/cm^2. In this case, the thickness of a layer of wool at the conveyor is 0.06±0.01 m; the motion speed of conveyor is 0.1 m/s; the number of converters per bath is 8±1 pieces.

Empirical research has shown that using acoustic oscillations when washing wool reduces water consumption by 30 times, productivity of fat for washing water increases to 90 %, the complete disinfection of wool is achieved. The technical water remains clean and can be used in a closed cycle. For control of the unwashed wool, breaking load was 802.6 sN, and the relative strength – 4.68 sN/Tex. For the wool that had been treated with acoustic oscillations, breaking load was 796.8 sN, and the relative strength – 4.3 sN/Tex.

The performance efficiency of a given technology is limited by the thickness of a layer of wool at the conveyors, which is a shortcoming. Further research would make it possible to create waste-free, environmentally friendly, and energy-saving technology for the primary treatment of wool.

6. Conclusions

1. To obtain the minimum reflection coefficient of the acoustic wave from a wool-liquid layer, shielded by the conveyor's gratings, less than $\left|\bar{R}\right|_{ref}<0{,}1,$ it is necessary to use the ratio of the grating's rods radius to its period within $R/l\sim0.14$. Reducing the power of a sound wave, reflected from a layer of wool-liquid, by less than 1 % is possible for the following parameters of the grating: $R\approx0.8$ mm, $l=5.7$ mm.

2. Continuous washing of wool in a wool-washing machine with flat hydrodynamic emitters should be performed at the following parameters of acoustic oscillations in a washing solution: frequency of the sound field is 1.1±0.1 kHz; the sound intensity is 1.1±0.01 W/cm^2; thickness of the wool layer on the conveyor is 0.06±0.01 m; motion speed of the conveyor is 0.1 m/s; the number of converters per bath is 8±1 pieces. Such parameters make it possible to obtain the quality of washed wool with the residual fat on fibers within 1.5 % while it is 2 % in line with GOST.

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