Modeling the water filtration rate during the process of squeezing leather

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Abstract. Mathematical models of changes in the rate of water filtration during the process of roller squeezing of leather were determined. It was revealed that the graphs of the mathematical models obtained correspond to experimental diagrams obtained by squeezing various wet materials. From the point of view of water motion, the roll contact zone (a squeezing area) is divided into four sections (phases). It was revealed that the filtration rate in the first two sections of the roll contact zone increases from an initial negative value to a maximum positive value, and in the last two sections of the roll contact zone, it decreases from a maximum value to a certain negative value.

1 Introduction

For many branches of industry, the task of squeezing (water removal) is of great practical importance. For example, in leather production, the quality of the product is directly related to the pressing process. Besides, solving the problem of environmental safety is impossible without solving the problem of wastewater disposal.

Mathematical models of the process of pressing wet materials are obtained by joint solutions to contact and hydraulic problems. In this case, contact problems consist of studying the phenomenon of the interaction of wet material with working rolls, and hydraulic problems consist of studying the water filtration in wet material and elastic coating of rolls. References [1-13] are devoted to solving contact and hydraulic problems of roller pressing of wet materials.

The studies in [14,15] are devoted to solving contact and hydraulic problems of roller pressing of leather, which take into account the deformation and filtration characteristics of the semi-finished leather product after chrome tanning [16, 17].

In [20], the rates of water filtration during the process of roller squeezing of leather were theoretically determined. Analysis of the theoretical curve of changes in filtration rate (Figure 1, curve 1) showed that they do not correspond to the experimental diagrams (Figure 1, curve 2) obtained in [18-20].

This study is devoted to refining the mathematical model of the water filtration rate obtained in [15], taking into account experimental diagrams of water filtration rates.

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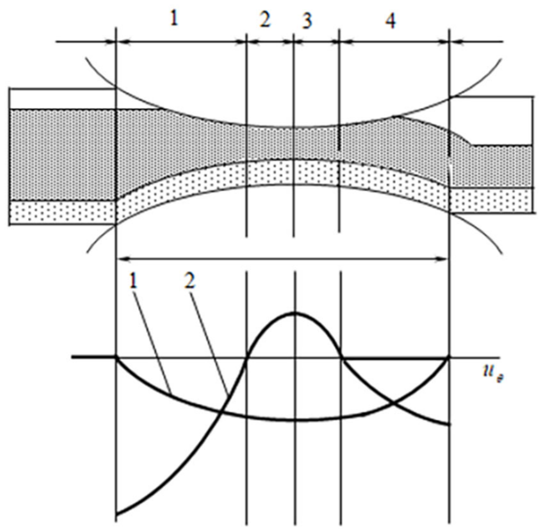

Fig. 1. Graphs of change in filtration rates: 1 - theoretical, 2 – experimental.

2 Materials and methods

A symmetrical two-roll module as the one given in [15], in which the working rolls with radii R have an elastic coating made of technical cloth with a thickness of H is considered; the leather layer has an initial thickness of δ_1 (Figure 2).

In the two-roller module under study, the leather interacts with pairs of rolls along the roll contact curves.

From the point of view of water motion, the contact (squeezing) zone is divided into four phases [18, 20].

Phase 1 begins when the leather or felt is saturated with water and ends when both become saturated. Here, the factors determining the flow of water are surface absorption and capillary phenomena.

Phase 2 begins when both materials are saturated and it ends when the external load reaches its maximum. Here a flow of water from the skin into the coating occurs.

Phase 3 begins when the external load reaches its maximum and ends when the pressure in the pores on the surface of the skin becomes negative.

Phase 4 begins when the pressure in the pores on the surface of the skin becomes negative and it ends when the external load is removed, that is, at the time the leather and cloth leave the squeezing zone. In this area, the leather and felt expand, and water moves from the felt into the leather, which leads to an increase in its moisture content.

From Figures 1 and 2 it follows that the roll contact curve (of each roll) consists of sections (phases) 1, 2, 3, and 4 [15, 20], corresponding to segments A_1A_2, A_2A_3, A_3A_4, and A_4A_5.Let the equation of the roll contact curve be given in polar coordinates $r_i = r_i(\theta_i)$ $i = \overline{1,4}$ is the index denoting the number of the section.

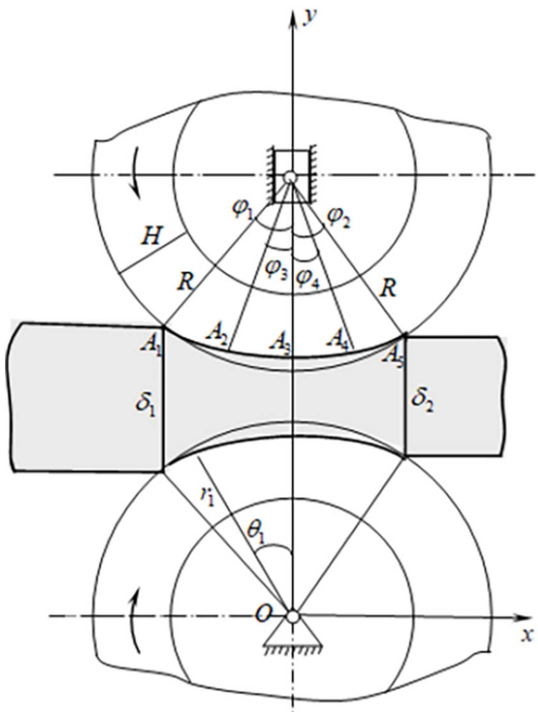

Fig. 2. Scheme of a two-roll module of a squeezing machine.

According to Figure 2

$$-\varphi_1 \le \theta_1 \le -\varphi_3,\ \ -\varphi_3 \le \theta_2 \le 0,\ \ 0 \le \theta_3 \le \varphi_4,\ \varphi_4 \le \theta_4 \le \varphi_2,$$

where $\varphi_1, \varphi_2 -$ are the contact angles, $\varphi_3 -$ is the angle separating sections 1 and 2, $\varphi_4 -$ is the angle separating sections 3 and 4.

Let us consider the process of water filtration in section 1. In this zone, the wet material is compressed, so the water passes from it into the roll coating along the polar angle.

According to [15], the fluid velocity along the Ox-axis in section 1 has the following form:

$$v_{1x} = \left(\frac{\alpha_1}{3\beta_1^2}(\theta_1^3 + C_1^*) \right) \sin\theta_1, \tag{1}$$

where

$$\alpha_1 = \frac{2v_l R\cos^2\varphi_1}{3\delta_1(1+m_1\gamma_1)}, \quad \beta_1^2 = \frac{2}{3}(1+m_1\gamma_1\cos\varphi_1), \tag{2}$$

here $m_1 = \dfrac{2n_1 H\cos\varphi_1}{n_1^*\delta_1}$, $n_1, n_1^* -$ is the coefficient of hardening of the points of cloth and leather under compression, $\gamma_1 -$ is the relation of the deformation rate of the cloth to the velocity of leather under compression, $v_l -$ is the velocity of leather.

Considering $v_{1x}(-\varphi_3) = 0$, we determine:

$$v_{1x} = a_1(\theta_1^3 + \varphi_3^3)\sin\theta_1, \tag{3}$$

where $a_1 = \dfrac{2v_l R\cos^2\varphi_1}{3\delta_1\,(1+m_1\gamma_1)(1+m_1\gamma_1\cos\varphi_1)}$.

Note that

$$v_{1y} = v_{1x} ctg\theta_1 .$$

Then, we obtain

$$v_{1y} = a_1(\theta_1^3 + \varphi_3^3)\cos\theta_1, \tag{4}$$

With known values of terms v_{1x} and v_{1y}, the rate of water filtration along the polar angle is determined by the following formula:

$$v_{1\theta} = \sqrt{v_{1x}^2 + v_{1y}^2} .$$

Then, we obtain

$$v_{1\theta} = a_1(\theta_1^3 + \varphi_3^3), \quad -\varphi_1 \le \theta_1 \le -\varphi_3, \quad . \tag{5}$$

From here, we find that $v_{1\theta}(-\varphi_1) = -a_1(\varphi_1^3 - \varphi_3^3).$

Thus, the filtration rate in section 1 increases from $-a_1(\varphi_1^3 - \varphi_3^3)$ to zero.

Similarly to formula (1), for section 2 we have:

$$v_{2x} = \left(\frac{\alpha_1}{3\beta_1^2}(\theta_2^3 + C_2^*\right)\sin\theta_2,$$

or subject to condition $v_{2x}(-\varphi_3) = 0$

$$v_{2\theta} = a_1(\theta_1^3 + \varphi_3^3), \quad -\varphi_3 \le \theta_2 \le 0, \ . \tag{6}$$

From here, we find that $v_{2\theta}(0) = a_1\varphi_3^3.$

Thus, the filtration rate in section 2 increases from zero to the maximum value $a_1\,\varphi_1^3$.

Similar to formulas (3) - (5), for section 3 we have:

$$v_{3x} = a_2(\varphi_4^3 - \theta_3^3)\sin\theta_3, \tag{7}$$

$$v_{3y} = a_2(\varphi_4^3 - \theta_3^3)\cos\theta_3, \tag{8}$$

$$v_{3\theta} = a_2(\varphi_4^3 - \theta_3^3), \quad 0 \le \theta_3 \le \varphi_4, \tag{9}$$

where

$$a_2 = \frac{2v_l R\cos^2\varphi_2}{3\delta_2\,(1+m_2\gamma_2)(1+m_2\gamma_2\cos\varphi_2)}, \quad m_2 = \frac{2n_2 H\cos\varphi_2}{n_2^*\delta_2},$$

here n_2, n_2^* – are the coefficients of hardening of the points of cloth and leather under recovery, γ_2 – is the ratio of the cloth deformation rate to the velocity of leather under recovery.

From here, we find that $v_{3\theta}(0) = a_2\varphi_4^3.$

Thus, the filtration rate in section 3 decreases from the maximum value $a_2\varphi_4^3$ to zero. From equalities (6) and (9), it follows that $v_{2\theta}(0) = v_{3\theta}(0)$ or $a_1\varphi_3^3 = a_2\varphi_4^3$. From here, we find the relationship between angles φ_3 and φ_4 in the following form:

$$\varphi_4 = \sqrt[3]{\frac{a_1}{a_2}}\varphi_3. \tag{10}$$

Similarly to formula (9), for section 4 we have:

$$v_{4\theta} = a_2(\varphi_4^3 - \theta_4^3), \quad \varphi_4 \le \theta_4 \le \varphi_2. \tag{11}$$

From here we find that $v_{4\theta}(\varphi_4) = 0$ and $v_{4\theta}(\varphi_2) = -a_2(\varphi_2^3 - \varphi_4^3)$.

Thus, the filtration rate in section 4 decreases from zero to $-a_2(\varphi_2^3 - \varphi_4^3)$.

3 Results

Mathematical models of the water filtration rate during the process of roller squeezing of semi-finished leather products after chrome tanning were determined. The graphs of the mathematical models obtained correspond to experimental diagrams plotted when squeezing various wet materials. The study of the squeezing process based on these models makes it possible to find the appropriate parameters for roller squeezing of leather with sufficient accuracy, necessary for the rational design and operation of squeezing machines.

4 Conclusions

From the point of view of water motion, the contact zone of the rolls (a squeezing area) is divided into four sections (phases). Analysis of the mathematical models obtained showed that the filtration rate at the initial point of the roll contact zone has the negative value $-a_1(\varphi_1^3 - \varphi_3^3)$. In the first two sections of the roll contact zone, first, it increases to the maximum value $a_1\varphi_1^3$, then in the last two sections of the roll contact zone it decreases from the maximum value to the negative value $-a_2(\varphi_2^3 - \varphi_4^3)$.

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