Increase Hydraulic Pressure by Compressing the Roller

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Abstract: The results of the study of hydraulic pressure in the roll squeezing of wet materials are given. Mathematical models of hydraulic pressure distribution in the squeezing zone are developed. It is revealed that the hydraulic pressure in the compression zone increases from zero at the initial contact point to a maximum at a point lying on the line of centers. The distribution patterns of hydraulic pressure in the strain restoration zone depend on the length of its part, where the fluid flows from the wet material into the roll coating.

Introduction

In many industries, roll technological machines are widely used for the mechanical processing of various materials. A special group is roller machines for squeezing wet materials.

In the process of roller squeezing of wet materials, the simultaneous occurrence of two phenomena is observed - contact interaction and moisture filtration. At the same time, a change in the indicators of contact interaction affects the change in moisture filtration, and vice versa. Therefore, the study of one of the phenomena without taking into account the other does not allow one to obtain reliable parameters of the process of roller squeezing of wet materials. Accordingly, to describe the roll squeezing of wet materials, it is necessary to jointly solve two problems: the first is contact interaction in two-roll modules (contact problem); the second is moisture filtration in a deformable inhomogeneous porous medium (hydraulic problem).

The identity of the laws that take place during the extraction of various materials causes a desire to reveal the physical picture of the phenomenon of moisture squeezing. Many researchers have tried to describe the movement of a liquid during its roll squeezing [1–4]

References [5-10] are devoted to the study of the phenomenon of contact interaction under the roll squeezing of wet materials. Mathematical models of the shape of roll contact curves, friction stresses, and distribution of contact stresses in a generalized two-roll module are developed in these studies.

One of the main hydraulic problems of the theory of roller squeezing of fibrous materials is the modeling of the hydraulic pressure distribution in the squeezing area [2].

An analysis of the studies devoted to the hydraulic problems of wet materials roll pressing [5-11] showed that the existing models of hydraulic pressure distribution in the pressing area were obtained with the introduction of models of roll equipment and materials that do not correspond to the real physical phenomena of wet materials roll pressing. They do not consider the presence of roll coating. However, in roll squeezing machines at least one of the rollers has an elastic coating. Therefore, the existing models of hydraulic pressure distribution do not allow the disclosure of the hydraulic phenomenon of wet materials roll pressing.

In [20], analytical dependencies were determined that describe the distribution patterns of the hydraulic pressure in the pressing area for a symmetrical two-roll module. In order to further develop theoretical concepts, [1-3], the object of study is a generalized two-roll module, in which the rolls are located relative to the vertical line with an inclination to the right at an angle of β, have unequal diameters $(D_1 \neq D_2)$ with elastic coatings, and a layer of wet (processed) material has a uniform thickness and is fed tilted downward with respect to the line of centers at an angle of γ_1 (Fig. 1).

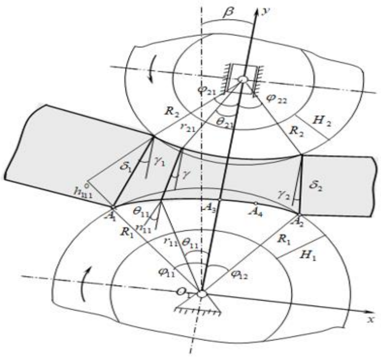

Fig. 1 Scheme of a two-roll moduleof squeezing machine

Materials and methods

The lower roll contact curve (curve A_1A_2) consists of two zones A_1A_3 and A_3A_2. In zone A_1A_3, the fibrous material and the roll coating are compressed, and in A_3A_2 the strain is restored.

Let us first consider the process of fluid filtration in zone A_1A_3.

The equation of the contact curve of the lower roll in the compression zone for the considered two-roll module has the following form [4]:

$$r_{11} = \frac{R_1}{1+k_{11}\lambda_{11}}\left(1+k_{11}\lambda_{11}\frac{\cos(\varphi_{11}+\gamma_1)}{\cos(\theta_{11}+\gamma)}\right), \quad -(\varphi_{11}+\gamma_1) \le \theta_{11}+\gamma \le 0, \tag{1}$$

$$k_{11} = \frac{m_{11}H_1\sin(\varphi_{11}+\varphi_{21})}{m_1^*\delta_1\sin(\varphi_{21}-\gamma_1)}, \quad \lambda_{11} = \frac{A_{11}^*m_{11}^*(\Delta l_{11})_{cp} - (A_{11}(1-m_{11}) - A_{11}^*(1-m_{11}^*))h_{11}^0}{A_{11}m_{11}(\Delta l_{11})_{cp} + (A_{11}(1-m_{11}) - A_{11}^*(1-m_{11}^*))H_1};$$

$$h_{11}^0 = \delta_1\frac{\sin(\varphi_{21}-\gamma_1)}{\sin(\varphi_{11}+\varphi_{21})}; \quad (\Delta l_{11})_{cp} = R_1\cdot\left(1-\frac{\sin 2(\varphi_{11}+\gamma_1)}{2(\varphi_{11}+\gamma_1)}\right),$$

here m_{11} – is the coefficient of strengthening of the points of the elastic coating of the lower roll under compression, m_1^* – is the coefficient of strengthening of the points of the processed material under compression.

Hence

$$r'_{11} = \frac{k_{11}\lambda_{11}R_1}{1+k_{11}\lambda_{11}}\cos\varphi_{11}\frac{\sin\theta_{11}}{\cos^2\theta_{11}}. \tag{2}$$

In zone A_1A_3, the fibrous material is compressed, so the fluid flows from it into the roll coating along the polar angle [2, 12].

The process of fluid flow is considered continuous and steady.

The feed rate of the fibrous material in the contact area is constant and equal to v_m.

The fluid rate in the contact area is variable and equal to [12]:

$$u_{11\theta} = -b_{11}((\varphi_{11}+\gamma_1)^3 + (\theta_{11}+\gamma)^3), \quad -(\varphi_{11}+\gamma_1) \le \theta_{11}+\gamma \le 0, \tag{3}$$

where

$$b_{11} = \frac{v_m R_1\cos(\varphi_{11}+\gamma_1)}{3h_{11}^0(1+k_{11}\lambda_{11})(1+k_{11}\lambda_{11}\cos(\varphi_{11}+\gamma_1))}, \quad h_{11}^0 = \delta_1\frac{\sin(\varphi_{21}-\gamma_1)}{\sin(\varphi_{11}+\varphi_{21})}.$$

In [2], assuming the working hypothesis of the orthogonality of the maximum and minimum porosity, the applicability of the generalized Darcy law for an anisotropic medium was established

$$\frac{\partial P_n}{\partial n} = -\upsilon\frac{u_\theta}{K_\theta}, \tag{4}$$

with filtration factor

$$\frac{1}{K_\alpha} = \frac{\cos^2\alpha}{K_{\max}} + \frac{\sin^2\alpha}{K_{\min}},$$

where P_n, u_θ – are the hydraulic pressure and filtration rate in direction n; υ – is the fluid viscosity coefficient; $K_{\max}$ – is the maximum filtration coefficient in the direction across the surface of the material (along the Oy axis); $K_{\min}$ – is the minimum

filtration coefficient in the direction along the warp threads of the material (along the Ox axis).
According to this dependence, the filtration direction angle varies within $0 \le \alpha \le 90^o$. On roller squeezing machines, where the rollers have an elastic coating, at each point of the roller contact curve, the resulting filtration rate is directed relative to the direction of the material feed at some angle of $90^o - \alpha$, close to the polar angle of θ [2]. Therefore, for this case, we can take $90^o - \alpha = \theta$ [12]. Then the expression for the filtration coefficient takes the following form:

$$\frac{1}{K_\theta} = \frac{\sin^2\theta}{K_{\max}} + \frac{\cos^2\theta}{K_{\min}}. \qquad (5)$$

With formulas (3), (4), and (5), we obtain

$$\frac{\partial P_{11n}}{\partial n_{11}} = \upsilon b_{11}\left(\frac{\sin^2(\theta_{11}+\gamma)}{K_{11\max}} + \frac{\cos^2(\theta_{11}+\gamma)}{K_{11\min}}\right)((\varphi_{11}+\gamma_1)^3 + (\theta_{11}+\gamma)^3)$$

assuming $\cos^2(\theta_{11}+\gamma) \approx 1-(\theta_{11}+\gamma)^2$ и $\sin^2(\theta_{11}+\gamma) \approx (\theta_{11}+\gamma)^2$

$$\frac{dP_{11n}}{d(\theta_{11}+\gamma)} = \frac{\upsilon b_{11}}{K_{11\min}}\left(1 - \frac{K_{11\max}-K_{11\min}}{K_{11\max}}(\theta_{11}+\gamma)^2\right)((\varphi_{11}+\gamma_1)^3 + (\theta_{11}+\gamma)^3)\frac{dn_{11}}{d(\theta_{11}+\gamma)}. \quad (6)$$

From Fig. 1, it follows that $n_{11} = r_{11}\cos(\theta_{11}+\gamma)$.
Hence

$$\frac{dn_{11}}{d(\theta_{11}+\gamma)} = r'_{11}\cos(\theta_{11}+\gamma) - r_{11}\sin(\theta_{11}+\gamma)$$

or considering equalities (1) and (2)

$$\frac{dn_{11}}{d(\theta_{11}+\gamma)} = -\frac{R_1}{1+k_{11}\lambda_{11}}\sin(\theta_{11}+\gamma) \approx -\frac{R_1}{1+k_{11}}(\theta_{11}+\gamma).$$

With this in mind, from equality (6) we obtain

$$\frac{dP_{11n}}{d(\theta_{11}+\gamma)} = -\frac{\upsilon R_1 b_{11}}{(1+k_{11}\lambda_{11})K_{11\min}}\left(1 - \frac{K_{11\max}-K_{11\min}}{K_{11\max}}(\theta_{11}+\gamma)^2\right)\times$$
$$\times((\varphi_{11}+\gamma_1)^3 + (\theta_{11}+\gamma)^3)(\theta_{11}+\gamma)$$

or being limited to the terms of the third power relative to $(\theta_{11}+\gamma)$

$$dP_{11n} = \frac{\upsilon R_1 b_{11}(\varphi_{11}+\gamma_1)^3}{(1+k_{11}\lambda_{11})K_{11\min}}\left(\frac{K_{11\max}-K_{11\min}}{K_{11\max}}(\theta_{11}+\gamma)^3 - (\theta_{11}+\gamma)\right)d(\theta_{11}+\gamma). \qquad (7)$$

After integration, we get

$$P_{11n} = c_{11}\left(\frac{K_{11\max}-K_{11\min}}{K_{11\max}}(\theta_{11}+\gamma)^4 - 2(\theta_{11}+\gamma)^2\right) + C_{11}, \qquad (8)$$

where

$$c_{11} = \frac{\upsilon v_m R_1^2\cos(\varphi_{11}+\gamma_1)(\varphi_{11}+\gamma_1)^3}{12K_{11\min}h_{11}^0(1+k_{11}\lambda_{11})(1+k_{11}\lambda_{11}\cos(\varphi_{11}+\gamma_1))}$$

Constant C_{11} is determined by initial condition

$P_{11n}(-(\varphi_{11}+\gamma_1)) = 0$:

$$C_{11} = \left(2(\varphi_{11}+\gamma_1)^2 - \frac{K_{11\max}-K_{11\min}}{K_{11\max}}(\varphi_{11}+\gamma_1)^4\right).$$

Then we obtain

$$P_{11n} = c_{11}((\varphi_{11}+\gamma_1)^2 - (\theta_{11}+\gamma)^2)\left(2 - \frac{K_{11\max}-K_{11\min}}{K_{11\max}}((\varphi_{11}+\gamma_1)^2 + (\theta_{11}+\gamma)^2)\right), \quad (9)$$

where $-(\varphi_{11}+\gamma_1) \le \theta_{11}+\gamma \le 0.$

This formula determines the patterns of distribution of hydraulic pressure along the contact curve of the lower roll in the compression zone.
The patterns of distribution of hydraulic pressure along the contact curve of the lower roll in the strain restoration zone are determined similarly:

$$P_{12n} = c_{12}((\varphi_{14}+\gamma_4)^2-(\theta_{12}+\gamma)^2)\left(2-\frac{K_{12\max}-K_{12\min}}{K_{12\max}}((\varphi_{14}+\gamma_4)^2+(\theta_{12}+\gamma)^2)\right), \quad (10)$$

where

$$0 \le \theta_{12}+\gamma \le \varphi_{12}+\gamma_2; \quad \varphi_{14}+\gamma_4 = \varsigma_1(\varphi_{12}+\gamma_2), \ 0<\varsigma_1 \le 1;$$

$$c_{12} = \frac{\upsilon v_m R_1^2 \cos(\varphi_{12}+\gamma_2)(\varphi_{12}+\gamma_2)^3}{12K_{12\min} h_{12}^0 (1+k_{12}\lambda_{12})(1+k_{12}\lambda_{12}\cos(\varphi_{12}+\gamma_2))}.$$

The patterns of distribution of hydraulic pressure along the contact curve of the upper roll are determined likewise. They have the following form:

$$P_{21n} = c_{21}((\varphi_{21}-\gamma_1)^2-(\theta_{21}-\gamma)^2)\left(\frac{K_{21\max}-K_{21\min}}{K_{21\max}}((\varphi_{21}-\gamma_1)^2+(\theta_{21}+\gamma)^2)-2\right), \quad (11)$$

where

$$-(\varphi_{21}-\gamma_1) \le \theta_{21}-\gamma \le 0,$$

$$c_{21} = \frac{\upsilon v_m R_2^2 \cos(\varphi_{21}-\gamma_1)(\varphi_{11}-\gamma_1)^3}{12K_{21\min} h_{21}^0 (1+k_{21}\lambda_{21})(1+k_{21}\lambda_{21}\cos(\varphi_{21}-\gamma_1))};$$

$$P_{22n} = c_{22}((\varphi_{24}-\gamma_4)^2-(\theta_{22}-\gamma)^2)\left(\frac{K_{22\max}-K_{22\min}}{K_{22\max}}((\varphi_{24}-\gamma_4)^2+(\theta_{22}-\gamma)^2)-2\right), \quad (12)$$

where

$$0 \le \theta_{22}-\gamma \le \varphi_{22}-\gamma_2; \quad \varphi-\gamma_4 = \varsigma_2(\varphi_{22}-\gamma_2), \ 0<\varsigma_2 \le 1;$$

$$c_{22} = \frac{\upsilon v_m R_2^2 \cos(\varphi_{22}-\gamma_2)(\varphi_{22}-\gamma_2)^3}{12K_{22\min} h_{22}^0 (1+k_{22}\lambda_{22})(1+k_{22}\lambda_{22}\cos(\varphi_{22}-\gamma_2))}.$$

Thus, analytical dependencies (9)-(12) are determined, which describe the patterns of distribution of hydraulic pressure in the pressing zone for the generalized two-roll module shown in Fig. 1.

Graphs of changes in hydraulic pressure along the roll contact curve are shown in Fig.2.

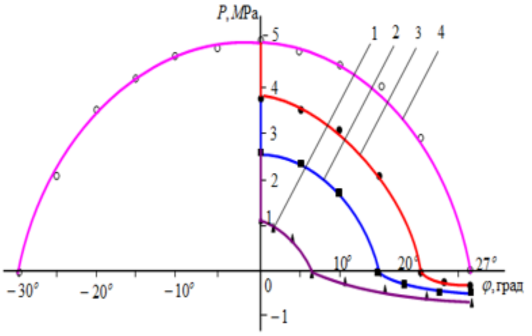

Fig. 2. Graphs of changes in hydraulic

pressure along the roll contact curve:

$$1-\varphi_{14}=\frac{1}{4}\varphi_{12}; \ 2-\varphi_{14}=\frac{1}{2}\varphi_{12};$$

$$3-\varphi_{14}=\frac{3}{4}\varphi_{12}, \ 4-\varphi_{14}=\varphi_{12}.$$

Results

Mathematical models of hydraulic pressure distribution in the squeezing zone were developed.

Conclusions

From the analysis of the calculated data and graphs, it follows that the hydraulic pressure in the compression zone increases from zero at the initial point of contact, to a maximum at a point lying on the line of centers. The distribution patterns of hydraulic pressure in the strain restoration zone depend on the length of its part, where the fluid flows from the wet material into the roll coating.

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