To the solution of some problems of roller pressing of sheet materials

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Abstract. The article is devoted to solving one of the basic hydraulic problems of the theory of roller pressing of sheet materials. Analytical dependencies are obtained that describe the distribution patterns of hydraulic pressure during roller squeezing of sheet materials. The analysis of the calculations showed that the obtained patterns of changes in hydraulic pressure are consistent with the theoretical conclusions and experimental diagrams obtained by other researchers.

1. Introduction
A special group in the technology of mechanical processing of materials performed in roller machines is the pressing of sheet material. Roller pressing of sheet materials consists of two phenomena - contact interaction and hydraulic interaction. The change in the indices of the first phenomenon affects the change in the indices of the second phenomenon and vice versa.

Therefore, the study of one phenomenon without considering the second one does not allow obtaining reliable parameters of the roller pressing process.

At present, there are many publications [1-5] devoted to solving problems of contact interaction in two-roll modules.

The main hydraulic problems of the theory of roller pressing of sheet materials in two-roll modules are analytical description of the distribution pattern of hydraulic pressures; modeling the residual moisture content of the squeezed material [6].

This article is devoted to the analytical description of the distribution pattern of hydraulic pressures during roller pressing of sheet materials.

Analysis of the analytical regularities of the distribution of hydraulic pressures [6-11], showed that they were obtained with the introduction of models of roller equipment and squeezed materials that do not correspond to the real physical phenomena of roller squeezing of sheet materials. In addition, they do not take into account the presence of the roller coating. However, in the squeezing two-roll modules, at least one of the rollers is coated with a water-permeable material. Besides, these solutions do not take into account the parameters of the contact interaction phenomenon. Consequently, the existing mathematical models of the distribution pattern of hydraulic pressure do not make it possible to reveal the hydraulic phenomenon of roller pressing of fibrous materials.
2. Analytical solutions to the assigned tasks

In a two-roll module, fluid filtration from sheet material into the coatings of the rollers occurs along the polar radius $r$ [6, 11]. The process of fluid flow is considered as continuous and steady state process. The speed of the sheet material in the contact area is constant and equals to $\nu_m$.

The zones of the roller contact relative to the centerline are divided into compression zone I and recovery zone II (figure 1).

![Figure 1. Two-roll module diagram.](image)

Change in the rate of fluid filtration in the compression zone along the axis $Ox$ is, according to [9]

$$u_{1x} = \frac{\delta - \delta(x)}{\delta(x)} \nu_m,$$  \hspace{1cm} (1)

where $\delta$ is the thickness of the material layer in the section $b - b$ at a zero fluid filtration rate (section $b - b$); $\delta(x)$ is the thickness of the material layer in the section $x - x$.

According to figure 1, thicknesses $\delta$ and $\delta(x)$ are expressed by the following formulas

$$\delta = H - 2r_1 (-\varphi_3) \cos \varphi_3,$$ \hspace{1cm} (2)

$$\delta(x) = H - 2r_1 \cos \theta_1, \quad -\varphi_1 \leq \theta_1 \leq 0,$$ \hspace{1cm} (3)

where $\varphi_3$ is the polar angle defining the section $b - b$; $H$ is the center distance of rollers; $\varphi_1$ is the entering angle.

Substituting expressions (2) and (3) into formula (1), we obtain:

$$u_{1x} = \frac{2r_1 \cos \theta_1 - 2r_1 (-\varphi_3) \cos \varphi_3}{H - 2r_1 \cos \theta_1} \nu_m.$$ \hspace{1cm} (4)

Then the fluid filtration rate in the compression zone along the polar radius has the form

$$u_{1r} = \frac{2r_1 \cos \theta_1 - 2r_1 (-\varphi_3) \cos \varphi_3}{(H - 2r_1 \cos \theta_1) \sin \theta_1} \nu_m.$$ \hspace{1cm} (5)
where $\nu_{ir}$ is the filtration rate of the fluid along the polar radius $r_i$.

In [6], accepting the working hypothesis of the orthogonality of the maximum and minimum porosity, the applicability of the generalized Darcy's law to an anisotropic medium was established

$$\frac{\partial P_r}{\partial r} = -\nu_r \frac{u_r}{k_{\theta}}$$

and the formula for the filtration coefficient was determined depending on the direction

$$\frac{1}{k_{\theta}} = \frac{\cos^2 \theta}{k_{\max}} + \frac{\sin^2 \theta}{k_{\min}}$$

where $P_r$, $u_r$ are the hydraulic pressure and filtration rate in direction $r$; $k_{\max}$ is the filtration coefficient (the maximum one) along the axis $Oz$; $k_{\min}$ is the filtration coefficient (the minimum one) along the axis $Ox$; $\nu_r$ is the fluid viscosity coefficient.

According to formulas (4), (5) and (6), for the compression zone we have

$$dP_r = -\nu_m \left( \frac{2r_1 \cos \theta_1 - 2r_1 (\varphi_1) \cos \varphi_1}{(H-2r_1 \cos \theta_1) \sin \theta_1} \right) \left( \frac{\cos^2 \theta_1}{k_{\max}} + \frac{\sin^2 \theta_1}{k_{\min}} \right) \frac{dr_1}{d\theta_1}, \quad -\varphi_1 \leq \theta_1 \leq 0.$$  

As stated in [6, 9], in the recovery zone, fluid filtration can continue up to a certain section $d-d$. Moreover, the sections $b-b$ and $d-d$ are at the same distance from the section $c-c$ (the centerline) [9]. Therefore, it can be assumed that in the recovery zone, fluid filtration occurs at the section $0 \leq \theta_2 \leq \varphi_3$ ($\varphi_1 < \varphi_3$).

Then, similar to (8), for the recovery zone we have

$$dP_{2r} = -\nu_m \left( \frac{2r_2 \cos \theta_2 - 2r_2 (\varphi_2) \cos \varphi_2}{(H-2r_2 \cos \theta_2) \sin \theta_2} \right) \left( \frac{\cos^2 \theta_2}{k_{\max}} + \frac{\sin^2 \theta_2}{k_{\min}} \right) \frac{dr_2}{d\theta_2}, \quad 0 \leq \theta_2 \leq \varphi_3.$$  

From expressions (7) and (8) it follows that the distribution pattern of hydraulic pressure in the process of roller squeezing depends on the equation of curves of the contact roller. The equation of curves of the contact roller is determined from the theory of contact interaction.

In [12], the equations of the curves of the contact roller were obtained in the following form

$$\begin{align*}
r_{11} &= \frac{R_1}{1 + \lambda_1} \left( 1 + \lambda_{11} \frac{\cos(\varphi_{11} + \gamma)}{\cos(\varphi_{11} + \gamma)} \right), \quad \gamma = \frac{\gamma_{11} \varphi_{11}}{\varphi_{11}}, \quad -\varphi_{11} \leq \theta_{11} \leq 0, \\
r_{12} &= \frac{R_1}{1 + \lambda_1} \left( 1 + \lambda_{12} \frac{\cos(\varphi_{12} + \gamma_{12})}{\cos(\theta_{12} + \gamma)} \right), \quad \gamma = \frac{m_1 \gamma_{12} \varphi_{12}}{\varphi_{12}}, \quad 0 \leq \theta_{12} \leq \varphi_{12}.
\end{align*}$$

These equations for the considered two-roll module take the form

$$\begin{align*}
r_1 &= \frac{R}{1 + \lambda_1} \left( 1 + \lambda_1 \frac{\cos \varphi_1}{\cos \theta_1} \right), \quad -\varphi_1 \leq \theta_1 \leq 0, \\
r_2 &= \frac{R}{1 + \lambda_2} \left( 1 + \lambda_2 \frac{\cos \varphi_2}{\cos \theta_2} \right), \quad 0 \leq \theta_2 \leq \varphi_3,
\end{align*}$$

where $\lambda_1$, $\lambda_2$ are the ratios of the rates of deformation of the roller surface layer and the layer of material under compression and recovery, respectively.

From the first equation of system (10) we obtain
Analytical dependencies were obtained that describe the distribution patterns of hydraulic pressure along the curves of the rollers in the recovery zone. Assuming that $2 \cos \theta_i \approx 2 - \theta_i^2$, $\tan^2 \theta_i \approx \frac{\theta_i^2}{1 - \theta_i^2}$ and taking into account $H = 2R \cos \phi_i + \delta_i$, equation (12) is transformed to the form

$$dP_1 = A_1 \left( \frac{1}{k_{\text{max}}^2} - \frac{c_1^2}{(1 + c_1^2) k_{\text{min}}^2} \right) \left( \frac{\phi_1^2 + \theta_i^2}{c_1^2 + \theta_i^2} \right) + \frac{1}{(1 + c_1^2) k_{\text{min}}^2} \left( \frac{\phi_1^2 - \theta_i^2}{1 - \theta_i^2} \right) d\theta_1,$$

where

$$A_1 = -\gamma_m R \lambda_1 \cos \phi_i \left(1 + \lambda_i\right), \quad c_1 = \frac{\delta_i \left(1 + \lambda_i\right) - R \phi_1^2}{R}.$$

Integrating (13) and considering the initial condition $P_1(\phi_i) = 0$, we obtain

$$P_1 = A_1 \left( \frac{1}{k_{\text{max}}^2} - \frac{c_1^2}{(1 + c_1^2) k_{\text{min}}^2} \right) \left( \frac{\phi_1^2 + c_1^2}{c_1^2 + \phi_1^2} \right) \left( \arctg \frac{\theta_i}{c_1} + \arctg \frac{\phi_1}{c_1} - \arctg \frac{\theta_i + \phi_i}{c_1} \right) + \frac{1}{(1 + c_1^2) k_{\text{min}}^2} \left( \frac{1 - \phi_1^2}{1 + c_1^2} \right) \ln \left( \frac{(1 + \theta_i)(1 + \phi_i)}{(1 - \theta_i)(1 - \phi_i)} \right), \quad -\phi_i \leq \theta_i \leq 0. \quad (14)$$

Formula (14) determines the distribution patterns of hydraulic pressure along the curves of the contact rollers in the compression zone.

Similarly, we determine the distribution patterns of hydraulic pressure along the curves of the contact rollers in the recovery zone

$$P_2 = A_2 \left( \frac{1}{k_{\text{max}}^2} - \frac{c_2^2}{(1 + c_2^2) k_{\text{min}}^2} \right) \left( \frac{\phi_2^2 + c_2^2}{c_2^2 + \phi_2^2} \right) \left( \arctg \frac{\theta_2}{c_2} - \arctg \frac{\phi_2}{c_2} - \arctg \frac{\theta_2 - \phi_2}{c_2} \right) + \frac{1}{(1 + c_2^2) k_{\text{min}}^2} \left( \frac{1 - \phi_2^2}{1 + c_2^2} \right) \ln \left( \frac{(1 + \theta_2)(1 + \phi_2)}{(1 - \theta_2)(1 + \phi_3)} \right), \quad 0 \leq \theta_2 \leq \phi_3. \quad (15)$$

where

$$A_2 = -\gamma_m R \lambda_2 \cos \phi_2 \left(1 + \lambda_2\right), \quad c_2 = \frac{\delta_2 \left(1 + \lambda_2\right) - R \phi_2^2}{R}.$$

3. Conclusion

One of the basic hydraulic problems of the theory of roller pressing of sheet materials was solved. Analytical dependencies were obtained that describe the distribution patterns of hydraulic pressure under roller pressing of sheet materials.
The analysis of the calculations showed that the change in the hydraulic pressure obtained by formulas (14) and (15) is consistent with the theoretical conclusions and experimental diagrams obtained by other researchers.

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