Technological efficiency of the squeezing process

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Abstract. A theoretical model of residual moisture of the processed material has been developed, which allows obtaining reliable parameters of the squeezing process and assessing the technological efficiency of the squeezing process. It has been established that with an increase in the roller radius, the thickness of the contacting bodies and a decrease in the ratio of deformation of the contacting bodies, the residual moisture increases. It has been revealed that a decrease in the coefficient of deformation of the roller coating and an increase in the coefficient of deformation of the processed material lead to a decrease in residual moisture.

1 Introduction

Squeezing modules of technological machines in various industries are designed to remove moisture (squeeze) from the processed material after liquid operations to achieve the necessary moisture content for subsequent operations.

When creating new and modernizing existing squeezing modules of technological machines, increased attention must be paid to focusing on environmentally friendly production. The use of technologically advanced equipment, such as roller squeezing machines, should not only improve product quality but also contribute to water conservation.

The squeezing module differs from conventional roll modules in the presence of a certain moisture content in the material being processed and coatings of the rollers of the squeezing pair made of moisture-permeable material [1].

During the squeezing, under the impact of the pressing force, the elastic coatings of the rollers and the processed material are deformed and form the so-called roll contact curves. At each point of the roll contact curves, contact and hydraulic pressures arise, resulting in two phenomena simultaneously occurring in the contact zone of the squeezing model - contact interaction and moisture filtration [2]. A change in the indicators of one phenomenon leads to a change in the indicators of another. Consequently, the problem of modeling any phenomenon in the contact zone of the squeezing modules requires a joint solution to two types of problems of the squeezing process – contact one (contact interaction between deformable materials) and hydraulic one (moisture filtration in deformable porous media). One of the hydraulic problems is the mathematical modeling of the residual moisture of theprocess. Mathematical modeling of the residual moisture of the process was done in the

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pulp and paper industry, in the textile and in the leather industry [3-6]. The analysis shows that the existing mathematical models can be used in special cases of roller pressing [7].

The aim of the work is to develop a mathematical model of residual moisture, allowing to evaluate the technological efficiency of the pressing process.

2 Materials and methods

As an example, we consider a symmetrical squeezing module with a processed material of thickness δ_1 and drive rollers with a radius R and an elastic coating with a thickness H (Figure 1).

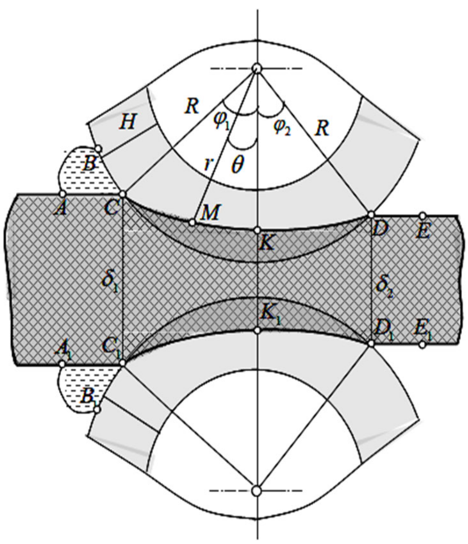

Fig. 1. Scheme of a symmetrical squeezing module.

Researchers of the roller pressing process divide the fluid flow area during the pressing process into four areas: the area of the water wedge; entry area; contact area; and exit area [8].

According to Figure 1, ABC and $A_1B_1C_1$ – are the areas of the water wedge. The difficulty in describing the fluid flow in this zone lies in the certainty of the position of boundaries AB and A_1B_1 [24]. Thus, the influence of this area is ignored and it is believed that the resistance to the fluid flow in this area is much less, than the resistance to flow in the entry area - ACC_1A_1A. The flow of fluid in the entry area occurs through boundaries AC and A_1C_1. CDD_1C_1C – is the contact area, or, in other words, the nip of the rollers (contact area). The flow of fluid in the contact area occurs through boundaries CD and C_1D_1. DEE_1D_1D – is the exit area.

According to previous studies, moisture filtration during the squeezing process is mainly characterized by the fluid flow in the contact area of the squeezing module. In the contact zone, the fluid flow from the processed material to the roller coatings, or vice versa, occurs through the upper and lower boundaries of the contact zone, that is, through the contact curves of the upper and lower rolls.

The contact area of the squeezing module consists of two zones - a compression zone, where the processed material and roller coatings are compressed, and a recovery zone, where they restore the deformation. The compression and recovery zones are separated by section KK_1 lying on the line connecting the centers of the rollers. Accordingly, the contact curve of each roll also consists of two parts - the entry one, lying in the compression zone, and the exit one, lying in the recovery zone. In this case, the entry part is determined by the nip angle φ_1, which sets the beginning of the contact zone, and the exit part is determined by the exit angle φ_2, which sets the end of the contact zone.

The flow of fluid in the contact zone happens along the roll contact curves, which are created by the deformation of the rollers' coating and the processed material. Therefore, variations in moisture content in the contact zone of the squeezing modules are also influenced by the deformation characteristics of the roller coatings and the processed material.

The deformation properties of materials processed in the squeezing module and materials coating the squeezing rollers are characterized by analytical relationships “stress-relative strain”, obtained as the results of experimental studies.

During compression, the liquid moves from the processed material into the roller coating. At the same time, the humidity of the contacting bodies changes. Based on this, the deformation properties of the contacting bodies during compression in the squeezing module will be characterized by the analytical dependencies "stress - relative deformation – relative humidity" [6]:

$$\sigma_{1c} = A_1 \varepsilon_{1c}^{a_1} V_{1c}^{c_1}, \qquad \sigma_{1m} = B_1 \varepsilon_{1m}^{b_1} V_{1m}^{e_1}, \tag{1}$$

where $\sigma_{1c}, \varepsilon_{1c}$ – are the stress and relative strain of the roll coating under compression, A_1, a_1, c_1 – are the coefficients characterizing the deformation properties of the roller coating under compression, V_{1c} – is the relative moisture content of the roller coating in the compression zone, $\sigma_{1m}, \varepsilon_{1m}$ – are the stress and relative strain of the processed material under compression, B_1, b_1, e_1 – are the coefficients characterizing the deformation properties of the processed material under compression, V_{1m} – is the relative moisture content of the processed material in the compression zone.

3 Results and discussion

According to Newton's law, at each point of the compression zone the conditions $\sigma_{1c} = \sigma_{1m}$, or taking into account equalities (1) are satisfied

$$A_1 \varepsilon_{1c}^{a_1} V_{1c}^{c_1} = B_1 \varepsilon_{1m}^{b_1} V_{1m}^{e_1}. \tag{2}$$

Hence, we obtain:

$$\frac{V_{1m}^{e_1}}{V_{1c}^{c_1}} = \frac{A_1}{B_1} \frac{\varepsilon_{1c}^{a_1}}{\varepsilon_{1m}^{b_1}}. \tag{3}$$

In the roll module, the following equality holds [23]:

$$\varepsilon_{1c} = \frac{\delta_1 k_1}{H(2-\varphi_1^2)} \varepsilon_{1m}, \tag{4}$$

where $k_1 -$ is the ratio of the compression strain rate of the roller coating to the compression strain rate of the processed material.

Considering equality (4), from equality (3) we obtain:

$$\frac{V_{1m}^{e_1}}{V_{1c}^{c_1}} = \frac{A_1}{B_1}\left(\frac{\delta_1 k_1}{H(2-\varphi_1^2)}\right)^{a_1} \varepsilon_{1m}^{a_1 - b_1}$$

or

$$V_{1m} = \alpha_1 V_{1c}^{\frac{c_1}{e_1}} \varepsilon_{1m}^{\frac{a_1-b_1}{e_1}}, \tag{5}$$

where

$$\alpha_1 = \left(\frac{A_1}{B_1}\left(\frac{\delta_1 k_1}{H(2-\varphi_1^2)}\right)^{a_1}\right)^{\frac{1}{e_{1\,1}}}. \tag{6}$$

The relative moisture content of the processed material and the roller coating in the compression zone is expressed as:

$$V_{1m} = \frac{W_{inm} - W_{1m}}{W_{inm}}, \quad V_{1c} = \frac{W_{inc} - W_{1c}}{W_{inc}}, \tag{7}$$

where $W_{inm} -$ is the moisture content of the processed material at the beginning of the contact area, $W_{1m} -$ is the moisture content of the processed material at the point of the compression zone, $W_{inc} -$ is the moisture content of the roller coating at the beginning of the contact area, $W_{1c} -$ is the moisture content of the roller coating at the point of the compression zone.

Substituting the expressions for relative moisture content into equalities (5), we obtain:

$$\frac{W_{inm} - W_{1m}}{W_{inm}} = \alpha_1 \varepsilon_{1c}^{\frac{a_1-b_1}{e_1}} \left(\frac{W_{inc} - W_{1c}}{W_{inc}}\right)^{\frac{c_1}{e_1}}.$$

Hence

$$W_{1m} = \left(1 - \frac{e_1 W_{inc} - c_1 W_{1c}}{e_1 W_{inc}} \alpha_1 \varepsilon_{1m}^{\frac{a_1-b_1}{e_1}}\right) W_{inm}. \tag{8}$$

During the squeezing process, the fluid removed from the processed material in the compression zone is determined by the difference in moisture contents W_{inm} and W_{1m}:

$$W_{rem} = W_{inm} - W_{1m}. \tag{9}$$

On the other hand, moisture content W_{inm} is equal to the amount of fluid flown from the processed material to the roller coating:

$$W_{1c} = W_{inm} - W_{1m}. \tag{10}$$

Let us substitute W_{1c} from equality (10) into equality (8):

$$W_{1m} = \left(1 - \frac{e_1 W_{inc} - c_1 (W_{inm} - W_{1m})}{e_1 W_{inc}} \alpha_1 \varepsilon_{1m}^{\frac{a_1-b_1}{e_1}}\right) W_{inm}.$$

Hence

$$W_{1m} = \left(1 - \frac{e_1 \alpha_1 W_{inc} \varepsilon_{1m}^{\frac{a_1 - b_1}{e_1}}}{e_1 W_{inc} + c_1 \alpha_1 W_{inm} \varepsilon_{1m}^{\frac{a_1 - b_1}{e_1}}}\right) W_{inm} \,. \tag{11}$$

From Figure 1, it follows that

$$\varepsilon_{1m} = \frac{2}{\delta_1}(r\cos\theta - R\cos\varphi_1) \tag{12}$$

where $r -$ is the mathematical model of the entry part of the roll contact curve, which has the following form [4]:

$$r = \frac{R}{1+k_1}\left(1 + k_1 \frac{\cos\varphi_1}{\cos\theta}\right), \quad -\varphi_1 \le \theta \le 0. \tag{13}$$

From equality (12), considering equality (13), we obtain:

$$\varepsilon_{1m} = \frac{2R}{\delta_1(1+k_1)}(\cos\theta - \cos\varphi_1)$$

or in the first approximation

$$\varepsilon_{1m} = \frac{2R}{\delta_1(1+k_1)}(\varphi_1^2 - \theta^2) \,. \tag{14}$$

Substituting the expression from equality (14) into equality (11), after transformations, we determine:

$$W_{1m} = \left(1 - \frac{e_1 \beta_1 W_{inc} (\varphi_1^2 - \theta^2)^{\frac{a_1 - b_1}{e_1}}}{e_1 W_{inc} + c_1 \beta_1 W_{inm} (\varphi_1^2 - \theta^2)^{\frac{a_1 - b_1}{e_1}}}\right) W_{inm} \,, \tag{15}$$

where

$$\beta_1 = \left(\frac{A_1}{B_1}\left(\left(\frac{k_1}{1+k_1}\right)\frac{R}{H(2-\varphi_1^2)}\right)^{a_1}\right)^{\frac{1}{e_{1\,1}}} \left(\frac{\delta_1(1+k_1)}{R}\right)^{\frac{b_1}{e_1}} . \tag{16}$$

Formula (15) describes the pattern of changes in the moisture content of the processed material in the compression zone of the squeezing module.

Let us differentiate equalities (15):

$$W'_{1m} = \frac{2 e_1 W_{inc}^2 W_{inm} \beta_1 (a_1 - b_1)(\varphi_1^2 - \theta^2)^{\frac{a_1 - b_1 - e_1}{e_1}} \theta}{\left(e_1 W_{1c} + c_1 W_{inm} \beta_1 (\varphi_1^2 - \theta^2)^{\frac{a_1 - b_1}{e_1}}\right)^2} \,.$$

$W'_{in} = 0$ for $\theta = -\varphi_1$ and $\theta = 0$.

It follows that the moisture content of the processed material in the compression zone decreases from $W_{1m}(-\varphi_1) = W_{inm}$ to $W_{1m}(0) = W_{\min}$.

From equality (15), we obtain:

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$$W_{\min} = \left(1 - \frac{e_1 \beta_1 W_{inc} \varphi_1^{\frac{2(a_1 - b_1)}{e_1}}}{e_1 W_{inc} + c_1 \beta_1 W_{inm} \varphi_1^{\frac{2(a_1 - b_1)}{e_1}}} \right) W_{inm} . \qquad (17)$$

In the recovery zone, the processed material may reabsorb some of the removed moisture from the roller coatings; therefore, changes in moisture content in the roller coating and the processed material may occur.

In [4, 13, 24] devoted to the study of roller squeezing of wet materials, the hypothesis "on the greatest efficiency of roller squeezing" is often used; according to it, the residual moisture of the squeezing process is the moisture content of the processed material at the end of the compression zone. It is argued that this hypothesis can be realized by selecting the type of roller coatings.

We accept this hypothesis. According to the accepted hypothesis, $W_{re} = W(0) = W_{\min}$, or considering expression (17):

$$W_{re} = \left(1 - \frac{e_1 \beta_1 W_{inc} \varphi_1^{\frac{2(a_1 - b_1)}{e_1}}}{e_1 W_{inc} + c_1 \beta_1 W_{inm} \varphi_1^{\frac{2(a_1 - b_1)}{e_1}}} \right) W_{inm} . \qquad (18)$$

Formula (18) defines a theoretical model of the residual moisture of the squeezing process, which allows us to obtain reliable parameters of the squeezing process and assess the technological efficiency of the spinning process.

Figures 2-4 show the dependence of the residual moisture content of the processed material on the radius of the roller and the thickness of the processed material.

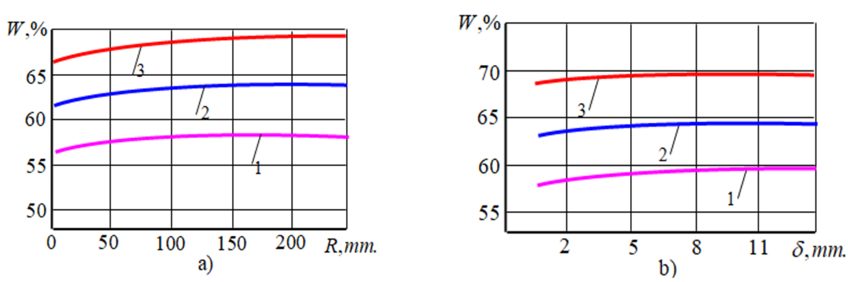

Fig. 2. Dependence of residual moisture: a) on the roller radius; b) on the thickness of the processed material at different values of initial moisture: $1 - W_{in} = 60\%,\ 2 - W_{in} = 65\%,\ 3 - W_{in} = 70\%$.

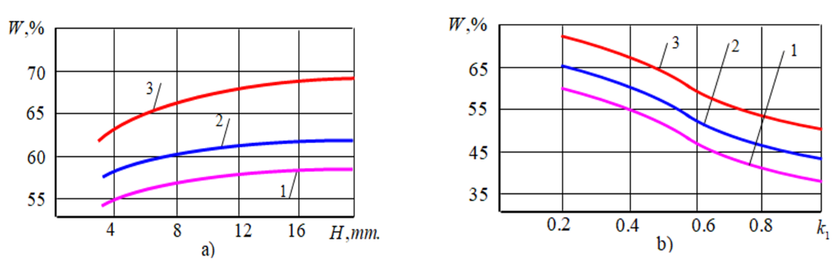

Fig. 3. Dependence of residual moisture: a) on the thickness of the roll coating; b) on the ratio of the rates of deformation during compression at different values of initial moisture: $1 - W_{in} = 60\%,$ $2 - W_{in} = 65\%,\ 3 - W_{in} = 70\%$.

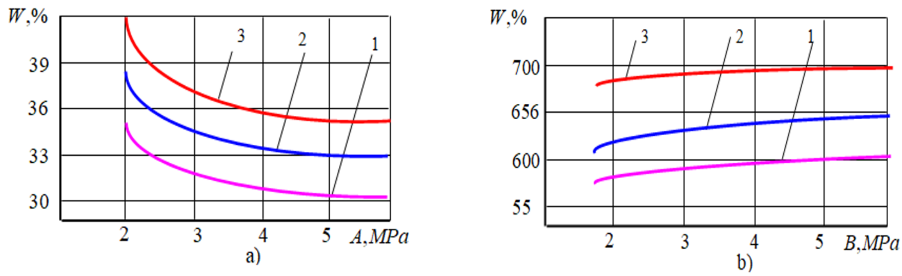

Fig.4. Dependence of residual moisture: a) on the coefficient of deformation of the roll coating; b) on the coefficient of deformation of the processed material: $1 - W_{in} = 60\%$, $2 - W_{in} = 65\%$, $3 - W_{in} = 70\%$.

4 Conclusion

A mathematical model of residual moisture has been developed, which allows obtaining reliable process parameters and assessing the technological efficiency of pressing.

Analysis of the calculated data showed that the residual moisture depends on the geometric and deformation properties, and the initial moisture content of the processed material and the roller coating.

Based on the analysis of the graphs of the dependence of residual moisture content on the factors of the squeezing process, shown in Figures 2-4, the following were revealed:

- with an increase in the radius of the roller, the thickness of the contacting bodies and a decrease in the ratio of deformation of the contacting bodies, the residual moisture increases;
- a decrease in the coefficient of deformation of the roller coating and an increase in the coefficient of deformation of the processed material lead to a decrease in residual moisture.

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