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Cell modeling of mass transfer in a dewatering process of fiber materials by distributed pressure

Modelowanie transportu masy w procesie usuwania wody z komórek materiałów włóknistych poprzez dystrybucję ciśnienia

Abstract
Our developed cell model of the mass transfer for the computation and prediction output parameters in a roll dewatering process of fibre materials by distributed pressure are presented. The model makes it possible to determine relationships between residual moisture content of fibre material and input parameters of the dewatering process.

Keywords: cell modelling, mass transfer, roll dewatering, dynamic pressure

Streszczenie
W pracy przedstawiono model transportu masy do wyznaczania parametrów obliczeniowych i wyjściowych procesu usuwania wody z materiałów włóknistych poprzez dystrybucję ciśnienia. Model pozwala wyznaczyć zależności pomiędzy wilgotnością resztkową materiale włóknistym a parametrami wejściowymi procesu odwadniania.

Słowa kluczowe: modelowanie, transport masy, odwadnianie rolkowe, ciśnienie dynamiczne

1. Introduction

The purpose of mathematical modelling of dewatering is to determine relationships between residual moisture content of fibre materials and the main process parameters. Traditionally, the machining process of long-length materials by distributed pressure in roll devices is carried out in static loading conditions with a constant technological pressure. With dynamic loading conditions in fluid flows moving through the capillary-porous structure of the fibre materials, cavitation phenomena and water hammer effects occur that improve the efficiency of dewatering. Our developed model describes fluid filtration through the fibre structure in static loading conditions and can be the first stage of dewatering modelling in dynamic loading conditions.

The theoretical basis of researches in this area, traditionally, contains differential equations of mass transfer, three-phase fabric structure consisting of solid particles, bound and free water, contact problem, describing the process of stress-strain state of the system and other factors that significantly affect the machining process of the fibre materials. The possibility to produce analytical solutions of this problem is due to the introduction of very significant estimates with sampling processes in space and time, which significantly reduce the versatility of these models and calculation algorithms as well as the prediction accuracy of output parameters in the investigated phenomena. The cell modelling method available in practice [1], based on the theory of Markov chains, makes it possible to solve the problem correctly and gives us an opportunity to create a model of fibre materials mechanical processing, which is applicable in a wide range of parameters for the investigated system.

2. Simulation

The main simulated elements of fibre material dewatering process in roll devices are shown in Fig. 1 where the material passes through the roller pair. Clearance h_{min} between the rolls is set, the value of which is less than the thickness h_{fab} of the fabric in a free state. The fabric consists of solid particles (the skeleton), bound and free water. The fabric skeleton is considered to be absolutely elastic. In the contact zone of rolls, the fabric goes through hydraulic pressure $H=H(x)$, characterised by filtration properties of the fabric, its speed and geometry of the contact zone, and the compression pressure $P=P(x)$, which is determined by the pressing force of rolls.

The cell modelling is associated with a spatiotemporal sampling process. The length of the rolls contact zone with fibre material enclosed between the sections *a-a* and *c-c* (Fig. 1), i.e. the portion where moisture removal occurs immediately, is partitioned into *m* cells of ideal displacement with equal length Δx, all the parameters are uniformly distributed in its volumes. At some point in time, a distribution of fluid particles along the length of the contact strip of the fibre material submitted to column vector of a liquid mass in the cells:

$$W = \begin{bmatrix} W_1 \\ W_2 \\ \ldots \\ W_j \\ \ldots \\ W_m \end{bmatrix} \tag{1}$$

where

W_j - the moisture content in the considered cell,

j - the number of the considered cell.

The transition from one state to another takes place through a transition time interval Δt, which is assumed to be sufficiently small so that the liquid particles during the transition can move from a given neighbouring cell only, but no further. During any single move i moisture distribution in the textile material along the length of the contact zone of rolls amounts to value W_i, which after the time Δt is changed and becomes W^{i+1}. Both of these conditions are related by the matrix equation:

$$W^{i+1} = PW^i \tag{2}$$

where

P – the transition matrix:

$$P = \begin{bmatrix} p_{s1} & p_{b2} & 0 & \ldots & 0 & 0 & 0 \\ p_{f1} & p_{s2} & p_{b3} & \ldots & 0 & 0 & 0 \\ 0 & p_{f2} & p_{s3} & \ldots & 0 & 0 & 0 \\ \ldots & \ldots & \ldots & \ldots & \ldots & \ldots & \ldots \\ 0 & 0 & 0 & \ldots & p_{s(m-2)} & p_{b(m-1)} & 0 \\ 0 & 0 & 0 & \ldots & p_{f(m-2)} & p_{s(m-1)} & p_{bm} \\ 0 & 0 & 0 & \ldots & 0 & p_{f(m-1)} & p_{sm} \end{bmatrix} \tag{3}$$

where

p_{sj}, p_{fj}, p_{bj} – the probability of remaining in j-th cell and moving forward and backward, respectively; each of the probabilities must satisfy the condition $0 \leq p \leq 1$ and their sum should be equal to unity.

Suppose the fluid particles move in capillary-porous structure of the fibre material with the velocity V_{liq}, and their macrodiffusion ratio is equal to D and characterises a spontaneous movement of the fluid particles, which leads to an equalisation of the concentrations throughout the occupied volume. Then, the probabilities of moisture moving from one cell to the next and previous, respectively, are:

$$p_f = v + d, \qquad p_b = d \tag{4}$$

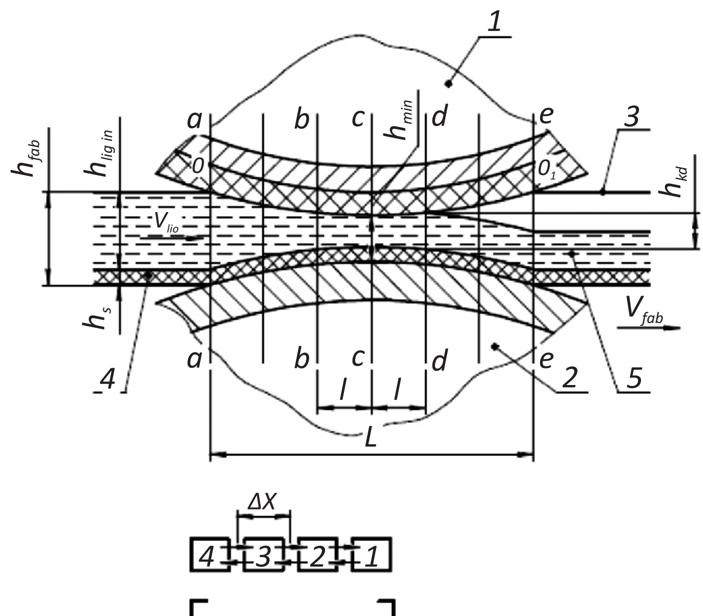
where

$$v = V_{liq} \frac{\Delta t}{\Delta x}, \quad d = D \frac{\Delta t}{\Delta x^2} \tag{5}$$

In the simulation of the process when fabric moving with constant velocity V_{fab} passes in a single transition distance Δx that is one cell, the values of Δt and Δx are dependent and related by the equation:

$$\Delta t = \frac{\Delta x}{V_{fab}} \tag{6}$$

The scheme of the cellular representation of fabric dewatering process by distributed pressure in rolls and the structure of the transition probabilities matrix are shown in Fig. 1.



$$P = \begin{bmatrix} 0 & 0 & 0 & 1-v \\ 0 & 0 & 1-v & v \\ 0 & 1-v & v & 0 \\ 1-v & v & 0 & 0 \end{bmatrix}$$

Fig. 1. The scheme of the cellular representation of fabric dewatering process by distributed pressure in rolls: 1, 2 – rolls; 3 – fibre material; 4 - solid particles of fabric (the skeleton); 5 – free water

3. Discussion

The cell model is constructed for the case when $d = 0$ and can be commented by an example of the moisture transfer process in cells 1 and 2. Suppose each side of the cell in the plan equals to Δx, and perpendicular sides to the plane of the figure equal to 1. The distance between the centres of the cells is also equal to Δx. Under the effect of hydraulic pressure, which arises in the textile material under compression, fluid displacement occurs from cell 1, which corresponds to an area with a minimum cross-section, in cell 2. For this transition, the probability of remaining in one cell is defined as the difference between the unit and the sum of the probabilities of all the other possible transitions, which is the sum of non-zero elements found in the column - $p_{s1}=1-v$. Accordingly, the probability of a transition in 2 cell p_{f1} equals to a proportion of the portable moisture weight v.

The transition matrix P is constructed taking into account that the velocity of the fluid in the entire length of the material in contact zone of rolls changes due to changes in the compressive and hydraulic pressure along the zone. The absolute velocity of the fluid at any section is related with the rate of fabric by equation:

$$V_{liq\ j} = V_{fab} \frac{h_{kd}}{h_{kj}} \tag{7}$$

If the mass of liquid in the cell grows larger than the limit, the excess of moisture content over the limit transfers into the next cells. It is realised in the model outside of matrix P by scanning and processing of the state vector W^{i+1} after transition. Similarly counted moisture removal from the fibre material in the input of rolls contact zone, i.e. removing excess moisture mass from the last cell of the chain.

On the output side of rolls, the pressure in the fibre material decreases gradually and the web thickness recovers. With the hydraulic pressure gradient termination, the pressure falls to zero, which gives rise to a partial vacuum at the output of rolls contact zone and rewetting process material occurs. Is set to [2], that the residual moisture of the fabric equals the moisture content in the cross section *d-d*. It should be noted that the moisture content in the cross section *d-d* corresponds to the moisture content in the cross section *b-b*, which are spaced symmetrically about the line *l*, which connects the rotation centres of rolls (Fig. 1).

Thus, we have developed the cell model of mass transfer in a dewatering process of fibre materials by distributed pressure [3, 4]. The model is implemented in a computer code and allows the calculation of residual moisture in fibre materials knowing the main parameters of the process.

4. Conclusions

Our developed cell model of mass transfer in the dewatering process of fibre materials by distributed pressure allows to consider all the basic features of the numerous process parameters.

The model is open and allows us to connect detailed descriptions of the individual components of the process. It can also provide a basis for the development of numerical description of the dewatering process in a dynamic mode of loading with a possibility of its implementation using computer analysis.

References

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