Find the optimal trajectory of the secondary discrete part to ensure efficient processing of cellulose fiber

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Abstract. This work presents the results of investigation of trajectories of elements implemented by electromechanical converter with discrete secondary part. The efficiency of implementation of various trajectories was evaluated.

1. Introduction

Modern polymeric materials, including cellulose and cellulose-containing ones, are complex heterogeneous (multicomponent and multiphase) systems whose properties are determined by the chemical structure of the components, the nature and intensity of interaction between them, as well as the micro- and macrostructure of the material. One of the promising ways to control these characteristics and, as a result, change the properties of cellulose-containing composite materials is to use nanoscale elements of the cellulose structure—nanocrystalline and nanofiber cellulose as a modifying component.

However, in order to fully utilize the cellulose fiber, it is necessary to weaken the complex structure of the cellulose by pretreatment. To date, a large number of different methods of pretreatment of cellulose fiber have already been developed. For pulp milling in industrial conditions, various types of grinding devices are most often used. Mills are widely used as a grinding device, which is confirmed in the published results of scientific works of recent years [1,2]. The mass is ground between the walls of the housing by a rotating disk with knives that have a smooth surface. There are studies in which ultrasound or conventional heat treatment [3,4], and sometimes a combination of different methods, are used to destroy the structure of the cellulose fiber, which undoubtedly increases the cost and complicates the processing process.

Among the methods presented above, hydrodynamic cavitation as a new promising method is the least studied and studied.

2. Main part

The efficiency of hydrodynamic cavitation is due to local increases in pressure and temperature. At the same time, the high energy effect depends on the formation, growth and collapse of cavitation cavities (bubbles) generated by pressure drops in the liquid raw material. In a number of publications for generating hydrodynamic cavitation, various configurations of diaphragms with holes with a diameter
of 1 mm appear [5]. The technology is based on the passage of liquid processed raw materials through holes with the occurrence of cavitation cavities at their boundaries.

![Figure 1. Schematic representation of diaphragms](image1)

In this study, an electromechanical converter with a discrete secondary part (ECDSP) was used to generate hydrodynamic cavitation in the pre-treatment of cellulose fiber. Unlike diaphragms, ECDSP is able to create a cavitation cloud under certain conditions throughout the entire volume of the working chamber, significantly accelerating the processing process, while increasing the energy efficiency of the process.

In addition to hydrodynamic cavitation, the treatment in ECDSP is accompanied by a radome of additional energy effects, including the impact of elements, magnetostriction and friction [6, 7].

![Figure 2. Section of electromechanical converter with discrete secondary part](image2)

In ECDSP, the secondary part represented by a large set of ferromagnetic elements moves in the treated medium under the influence of an external electromagnetic field. In turn, electromagnetic field, its force and direction is determined by combination of connected concentrated coils arranged in inductor slots.

The movement of the elements at a speed higher than critical causes a vacuum of the liquid. In the vacuum phase, a gap is formed in the liquid in the form of a cavity, which is filled with saturated liquid vapor. In the compression phase, under the influence of increased pressure and surface tension forces, the cavity collapses. A significant effect of cavitation processes is associated with a high concentration of energy released during the collapse process in the treated medium. At the moment of collapse, the gas pressure and temperature reach significant values, and according to some data reach 100 MPa and 1000 °C, respectively [8].

Thus, the first most important parameter of pulp grinding technology in ECDSP is the achievement of maximum speed by moving elements. A feature of the present device for implementing pulp pre-grinding technology is the possibility, when including various combinations of inclusion of coils or coil groups, of implementing unique motion paths inaccessible to similar installations, referred to in most scientific literature as vortex layer activators. In accordance with the classification proposed in [9] for a magnetic system of inductor machines similar to the configuration of a magnetic system of an electromechanical converter with a discrete secondary part, the efficiency of the device depends on the selected phase switching algorithm. Each individual path of the ferromagnetic elements may be useful
in the treatment of a particular liquid material. However, within the framework of this study, the speed of motion is of paramount importance, since achieving a speed close to or higher than a critical value allows intensifying hydrodynamic cavitation.

The first stage of the study was the modeling of various trajectories of the ferromagnetic element with parameterization of the speed and free run path. According to the previously presented works \cite{10}, the following system of differential equations was used to study the trajectory and motion parameters of the ferromagnetic element:

\[
\dot{x} = \frac{F_{3x}}{m_3} - \frac{1}{2m_3} c S_M \rho_x \sqrt{x^2 + y^2}; \\
\dot{y} = \frac{F_{3y}}{m_3} - \frac{1}{2m_3} c S_M \rho_y \sqrt{x^2 + y^2} - \frac{g V_3}{m_3} (\rho_3 - \rho_x).
\]

The study of the electromechanical converter with a discrete secondary part was carried out for the four most optimal and implemented control algorithms in two stages, using instantaneous values of variables. The optimality of the implemented algorithms is due to restrictions on the heating resistance of the coils, since with an increase in the current density in the coils, it is possible to achieve the speed of ferromagnetic elements significantly higher in a short-term mode. In the four combinations presented, the degree of heating of the coils allows the plant to be used in a long-term mode without disrupting the operation and breakdown of the insulation.

The order of the study was divided into two stages. At the first stage, based on the results of calculations, the position of the working ferromagnetic element was fixed at the boundaries of the given areas and the speed and length of the free run of the ferromagnetic element to contact the working chamber was calculated. At the second stage, coordinates of each new position of the ferromagnetic working element in the space of the working chamber were recorded, and frame-by-frame movement of the working element was built.

Simulation results based on the frame-by-frame trajectory of the single ferromagnetic element are shown in fig. 3-6.

**Figure 3.** Model of motion path of unit ferromagnetic element A

**Table 1.** Energy characteristics of motion path A

| I, A | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 | 19 | 20 |
|------|----|----|----|----|----|----|----|----|----|----|----|
| V_m, m/s | 2,6 | 2,9 | 3,7 | 4,7 | 5,2 | 6,1 | 7,1 | 7,5 | 8,2 | 8,7 | 9 |
| V_a, m/s | 0,6 | 0,7 | 0,76 | 0,91 | 1,1 | 1,2 | 1,5 | 1,7 | 1,9 | 2,1 | 2,4 |
Table 2. Energy characteristics of motion path B

| I, A | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 | 19 | 20 |
|------|----|----|----|----|----|----|----|----|----|----|----|
| V_m, m/s | 3,1 | 3,4 | 4,1 | 5,0 | 5,8 | 6,6 | 7,4 | 7,9 | 8,7 | 9,3 | 9,8 |
| V_a, m/s | 1,5 | 1,9 | 2,2 | 2,6 | 2,9 | 3,2 | 3,5 | 3,9 | 4,1 | 4,4 | 4,6 |

Table 3. Energy characteristics of motion path C

| I, A | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 | 19 | 20 |
|------|----|----|----|----|----|----|----|----|----|----|----|
| V_m, m/s | 3,2 | 3,5 | 4,2 | 5,3 | 5,9 | 6,8 | 7,8 | 8,3 | 9,2 | 9,7 | 10,2 |
| V_a, m/s | 0,5 | 0,6 | 0,7 | 0,89 | 0,98 | 1,1 | 1,3 | 1,6 | 1,7 | 1,9 | 2,1 |

Figure 4. Model of motion path of unit ferromagnetic element B

Figure 5. Model of motion path of unit ferromagnetic element C

Figure 6. Model of motion path of unit ferromagnetic element D
Table 4. Energy characteristics of motion path D

| I, A | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 | 19 | 20 |
|------|----|----|----|----|----|----|----|----|----|----|----|
| $V_m$, m/s | 3,5 | 3,8 | 4,4 | 5,6 | 6,2 | 7,2 | 8,1 | 8,7 | 9,5 | 10,1 | 10,3 |
| $V_a$, m/s | 0,6 | 0,64 | 0,71 | 0,82 | 0,94 | 0,97 | 1,1 | 1,4 | 1,5 | 1,7 | 1,9 |

According to a number of parameters of the studied trajectories, it can be concluded that in some cases an increase in the maximum speed does not lead to an increase in the length of the free run of the element with the speed necessary for the occurrence of a cavitation cloud in the path behind the element. Thus, in order to select the optimal path of motion, it is necessary to determine the fraction of the path in which a stable cavitation cloud will form behind the ferromagnetic element. The analysis of the movement of the single ferromagnetic element showed that the elements, when moving from one active pole to another, go through the acceleration and braking stages (fig. 7). The braking and acceleration path largely depends on the combination of coils included at each time point when the ferromagnetic element moves from one point to another. In this study, the proportion of the path of the element at which cavitation occurs was expressed through the trajectory coefficient.

Figure 7. Motion of the element in ascending and descending trajectory

Trajectory analysis yielded some averaged data showing the proportion of path travelled by the ferromagnetic element at a velocity below the critical, expressed trajectory coefficient shown in table 5.

Table 5. Dynamics of ferromagnetic element motion

| Trajectory type | Proportion of path travelled with cavitation |
|-----------------|-------------------------------------------|
| A               | 0,86                                      |
| B               | 0,91                                      |
| C               | 0,72                                      |
| D               | 0,6                                       |
As a result, trajectory analysis yielded some averaged data showing the proportion of path travelled by the ferromagnetic element at a velocity below the critical, expressed trajectory coefficient shown.

3. Conclusion
The analysis of the possible trajectories of the ferromagnetic elements of the ECDSP made it possible to draw some conclusions regarding the implementation of the pulp treatment process by hydrodynamic cavitation. Despite the importance of the speed of motion in the implementation of cavitation, in the treatment process itself, the time of action of hydrodynamic cavitation on cellulosic fiber is no less important. In other words, the greater the proportion of path travelled by the ferromagnetic element with the cavitation cloud, the longer the hydrodynamic cavitation can affect the cellulosic fiber in one cycle of motion of the secondary discrete part. Increasing the fraction of the cavitation trajectory will reduce the total processing time of the cellulosic fiber. In this study, trajectory B was selected as the most optimal.

The reported study was funded by RFBR according to the research project № 18-29-18064.

References
[1] Gavrilova A.S., Manayenkov O.V., Filatova A. E., Investigation of the effect of ultrasound on microcrystalline cellulose, Bulletin of Tver state technical university, 2015, pp. 60-66.
[2] Sarymsakov A. A., Baltayeva M. M., Nabiev D. S., Rashidova S. sh., Yugay S. M. Dispersed microcrystalline cellulose and hydrogels based on it // Chemistry of plant raw materials. 2004, №2, pp. 11-16.
[3] Gharehkhani S. Basic effects of pulp refining on fiber properties – A review / S. Gharehkhani, E. Sadeghinezhad, S.N. Kazi, H. Yarmand, A. Badarudin, M.R. Safaei, M.N.M. Zubir // Carbohydrate Polimers. 2015. 115. P. 785-803.
[4] Kerekes, R.J. Characterizing refining action in PFI mills / R.J. Kerekes, R.M. Soszynski, P.A.T. Doo // Tappi Journal. 4(3). 2005. P. 9-13.
[5] Ruly Terán Hilares, Gabriela Faria de Almeida, Muhammad Ajaz Ahmed, Felipe A.F. Antunes, Silvio Silvério da Silva, Jong-In Han, Júlio César dos Santos, Hydrodynamic cavitation as an efficient pretreatment method for lignocellulosic biomass: A parametric study, Bioresource Technology 235 (2017), pp. 301–308.
[6] Kuimov D., Minkin, M. The electromechanical converter in the systems of desulfurisation of crude oil, MATEC Web of Conferences, 2017.
[7] Kuimov D., Pavlenko, A., Minkin, M., Optimization of parameters of the electromechanical converter with a discrete secondary part, MATEC Web of Conferences, 2017.
[8] Piersol I. Cavitation. Moscow: Mir, 1975. - 95 p.
[9] Shevkunova A.V. Choice of optimization method for the tooth zone of the valve-inductor motor, New science: Problems and prospects, 2016, N. 3-2, pp. 248-251.
[10] Kuimov D., Minkin, M. Searching of the optimum modes for processing of various origin of cellulose fibers in the electromechanical converter with a discrete secondary part, AIP Conference Proceedings, 2019.