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Modelling of milling processes in knife grinding machines

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Modelling of milling processes in knife grinding machines

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Abstract. Knife grinding machines present the basic process equipment for fibrous material grinding in a pulp and paper industry. The article is devoted to research of hydrodynamic processes at milling. The theory of steam dynamics in this machine is considered. Researches with the use of modelling in program environment Ansys fluent are carried out. The results of the researches can be used to design and operate knife grinding machines and similar equipment, for example, in centrifugal pumps.

1. Introduction

Knife grinding machines are the main technological equipment for grinding fibrous materials in the pulp and paper industry. When grinding fibrous materials in mills, the main properties of the products are included. These machines belong to the most energy-intensive equipment in the production of paper, cardboard and wood boards [1-3]. Previously, the study of grinding processes was carried out in the works of Yu. D. Alashkevich, V.N. Goncharov and their students [4-7], as well as abroad [8-12]. The article studies the processes using simulation in the Ansys fluent software environment [13].

2. Theory of flow dynamics

In the study of flow dynamics, the following assumptions are accepted: knives and flutes are replaced by the objects in the form of rectangular blocks; rise of temperature and steam formation at milling is not taken into account; the fibrous weight is submitted to organic laws of hydrodynamics and is modelled as a Newtonian incompressible fluid with constant viscosity.

The hydrodynamics of pulp flows in a mill can be described by the Navier-Stokes equations [14]:

$$\frac{\partial \mathrm{v}_i}{\partial y_i} = 0 \tag{1}$$

$$\frac{\rho \partial \mathrm{v}_i}{\partial t} + \rho \mathrm{v}_j \frac{\partial \mathrm{v}_i}{\partial y_j} = -\frac{\partial p}{\partial y_i} + \mu \frac{\partial^2 \mathrm{v}_i}{\partial y_\mathrm{j} \partial y_\mathrm{j}}, \tag{2}$$

where ρ, μ = density and dynamic viscosity of the fibrous mass, p = pressure, v_i = velocity of the *i*-th point of the fibrous mass.

The two terms on the left side of equation (2) determine the unstable and convective acceleration, and the terms on the right side determine pressure and viscous forces. To solve such tasks, it is advisable to use the finite volume method implemented by the *Ansys fluent* computer program [13]. The flux field in the mill can be written as [15]:

$$V_i = \overline{V_i} + \text{v}_i{}' \quad (3)$$

$$P_i = \overline{P_i} + P_i{}' \quad (4)$$

Substituting the expressions (3) and (4) into the Navier-Stokes equations we get:

$$\frac{\partial \text{v}_i'}{\partial t} + \frac{\partial \overline{V_i}}{\partial t} + \frac{\text{v}_j' \partial \overline{V_i}}{\partial y_j} + \overline{V_j} \frac{\partial \text{v}_i'}{\partial y_j} + \overline{V_j} \frac{\partial \overline{V_i}}{\partial y_j} + \text{v}_j' \frac{\partial \text{v}_i'}{\partial y_j} = -\frac{1}{\rho} \frac{\partial P'}{y_i} - \frac{1}{\rho} \frac{\partial \bar{P}}{y_i} + \vartheta \nabla^2 \text{v}_i' + \vartheta \nabla^2 \overline{V_i} \quad (5)$$

To study equation (5) in relation to the flows in flutes of the mill garniture, it is necessary to simulate the flows.

3. Modelling of flows

To study the mass flows in the garniture, we introduce a fixed *XYZ* and a moving *xyz* coordinate system, so that the *Y* axis coincides with the axis of mill rotor rotation, and *Z* with the vertical axis. The origin of the *xyz* coordinate system coincides with the flute of the garniture. The relative velocity of the particle mass in the flute can be presented as following:

$$V_r = \text{v} - \Omega \cdot r \,, \quad (6)$$

where v = absolute mass particle velocity, $\Omega \cdot r$ = particle rotation speed relative to the moving coordinate system.

Using the transformation (6), we can write the Navier-Stokes equation for the relative velocity as follows [15]:

$$\frac{\partial V_r}{\partial t} = -\frac{1}{\rho} \nabla p + g + v \nabla^2 V_\text{r} - (2\Omega V_\text{r}) - (\Omega^2 r), \quad (7)$$

where $2\Omega V_\text{r}$, $\Omega^2 r$ = Coriolos and centrifugal acceleration respectively, g = acceleration of gravity.

For absolute speed it can be written:

$$\frac{\partial v}{\partial t} + v . \nabla \text{v} = -\frac{1}{\rho} \nabla p + g + v \nabla^2 v - (\Omega \cdot v). \quad (8)$$

Initial data for the calculation in the *Ansys fluent* software environment are presented in table 1.

Table 1. Calculation initial data.

Pulp model	Newtonian incompressible fluid
Pulp density, kg/m^3	990-1,000
The viscosity of the fibrous mass, Pas	0.001-0.1
Turbulence model	k-ε turbulence model
Mill rotor rotation frequency, t/m	600, 750, 1,000
Pressure at the exit, kPa	124, 188, 310
External and internal radii of the garniture knife belt, mm	200, 350
Flute dimensions (a×h×l), mm	3×4×150
The angle of the flute axis inclination to the radius of the garniture, degrees	20, 0, -20
Grid model	Hexagon elements, 284031 element in the flute section

4. Research results

With an increase in the rotor speed from 600 to 1,000 min^{-1}, the flow through the rotor's flute increases 2.3-5.4 times, depending on the pressure difference between the exit and the entrance of the flute (table 2). With an increase in the pressure drop between the exit and the entrance of the flute from 60 to 135 kPa, the flow through the flute decreases 1.4-1.5 times. The flow through the stator flute is almost independent of the rotor speed. With an increase in the pressure drop between the exit and the entrance of the cross-section flute from 60 to 135 kPa, the flow rate increases from 2.1 to 2.2 times. The sign "-" in terms of flow through the stator flute in tables 2,3 indicates the reverse direction of the flow - from the periphery to the centre of the garniture.

Table 2. Flow rate through the rotor/stator flute, l/s at various pressure drops.

Rotor speed, min^{-1}	Pressure drop Δp_c, kPa			
	60	80	100	135
600	0.110/-0.088	0.078/-0.128	0.045/-0.149	-0.035/-0.187
750	0.170/-0.087	0.151/-0.126	0.13/-0.45	0.110/-0.184
1,000	0.250/-0.085	0.225/-0.125	0.10/-0.43	0.183/-0.180

The average value of the flow rate in the rotor flute with an increase in the rotor speed from 600 to 1000 min^{-1} increases 2.4-2.6 times (table 3).

Table 3. The average value of the flow rate in the multi-root flute of the rotor/stator, m/s at different pressures between the exit and the entrance of the flute.

Rotor speed, min^{-1}	Pressure drop Δp_c, kPa			
	60	80	100	135
600	2.95/-2.35	1.87/-3.40	0.35/-4,55	-1.22/-5.92
750	5.04/-2.36	4.03/-3.42	3.12/-4,50	1.85/-5.86
1,000	7.18/-2.32	6.30/-3.30	5.55/-4,35	4.36/-5.51

With an increase in pressure drop from 60 to 135 kPa, the average value of the flow velocity in the inter-root flute of the rotor decreases 1.6-2.7 times. At the same time, the average flow rate in the cross-flute of the stator increases 2.3-2.6 times.

The flow rate in the inter-root flute of the rotor at a rotation frequency of 750 min^{-1} and a pressure difference of 60 kPa in sections of the flute along its length is shown in figure 1.

a) b) c) d) e) f) g)

Figure 1. The flow velocity in the rotor flute at a rotational speed of 750 min^{-1} and pressure difference between the exit and entrance of the flute of 60 kPa in the flute sections: a) 5 mm; b) 25 mm; c) 45 mm; d) 65 mm; e) 85 mm; f) 105 mm; g) 135 mm.

The nature of this speed varies significantly in sections of the flute. At the beginning of the flute, this flow is almost homogeneous (figure 1, a), then a region with an increased speed appears at the bottom of the flute (figure 1, c – 1, d). As the flow moves, this area shifts down towards the base of the garniture (figure 1, c). Then a centre with a high flow rate at the top of the flute is formed (figure 1, e). As the flow continues, the centre of increased speed at the bottom of the flute moves upwards (figure 1, d - 1, g), and the intensity of the flow at the top of the flute increases.

The average flow rate in the rotor flute at different angles of inclination to the radius at a pressure Δp_c = 80 kPa is presented in table 4.

Table 4. The average flow rate in the inter-root flute of the rotor, m/s at different angles of inclination to the radius.

Rotor speed, min^{-1}	β angle, degrees 20	0	- 20
600	2.24	1.87	1.58
750	4.87	4.03	3.18
1,000	7.58	6.30	5.53

Angle β is positive when the direction of rotation and angle coincide and angle β is negative when directions do not match.

The average flow rate changes with the change of the inclination angle of the knife flute to the garniture radius. When the angle of inclination is 200 in the direction of the rotor rotation, the flow velocity increases by 1.2 times (pumping mode). When the angle of inclination is 200 against the direction of the rotor rotation, the flow velocity decreases by 1.1 times (hold mode).

The speed in the multi-root flute of the rotor in the middle section along the length and frequency of the rotor rotation of 1000 min^{-1} is shown in figure 2.

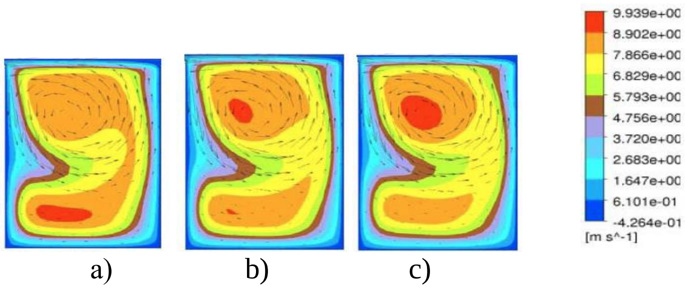

Figure 2. The flow rate in the rotor flute at a speed of 1000 min^{-1} and a pressure drop between the exit and the entrance of the flute: a) 60 kPa; b) 80 kPa; c) 100 kPa.

With an increase in pressure drop between the exit and the entrance of the flute, the nature of the velocity changes in the middle section of the flute. With a relatively small pressure drop (60 kPa), the highest flow rate is observed at the bottom of the flute. With an increase in pressure drop to 80-100 kPa, the highest flow velocity shifts up the interatal flute, and an increase in the differential leads to an increase in the area with an increased flow rate. The speed in the rotor flute at a rotational speed of 750 min^{-1} and a pressure drop between the exit and the entrance of the flute of 60 kPa is shown in figure 3.

This speed in the cross-flute of the rotor differs significantly in different sections of the flute. From the beginning of the flute this speed is almost uniform (figure 3, a). Then, an area with a negative flow velocity appears at the exit edge of the back edge of the knife, i.e. the flow is downward. Also, an area with a positive flow rate appears, i.e. the flow is directed vertically. The intensity of these flows increases along the course of the inter-root flute (figure 3, b - 3, g).

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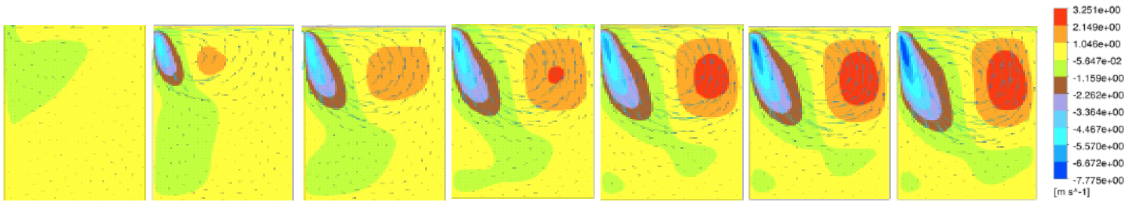


a) b) c) d) e) f) g)

Figure 3. The flow rate in the rotor flute in the vertical direction with a rotation frequency of 750 min^{-1} and a pressure drop of 60 kPa in the flute sections: a) 5 mm; b) 25 mm; c) 45 mm; d) 65 mm; e) 85 mm; f) 105 mm; g) 135 mm.

The average flow rate along the length of the flutes increases with the speed of the rotor. At the entrance to the flute the velocity increases sharply, reaches a maximum on the length of the flute of 5-10 mm. Then it monotonously rises by about 1.2-1.5 times along the flute (figure 4).

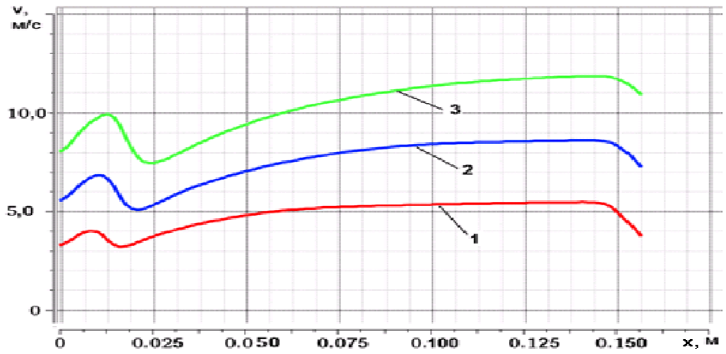
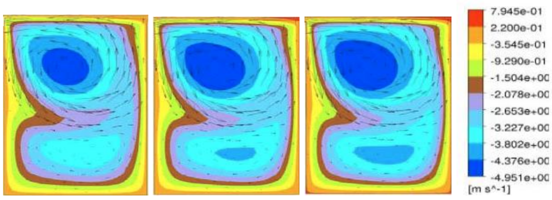


Figure 4. The average flow rate along the length of the rotor flute at rotational speed: 1 - 600 min^{-1}; 2 - 750 min^{-1}; 3-1,000 min^{-1}

The velocities in the interstitial flute of the stator in the middle section of the flute depend on the pressure drop between the exit and the entrance of the flute. In figure 5 two streams are visible at the top and bottom of the stator flute, the intensity of the upper stream is much higher than of the bottom one. With increasing pressure drop, the intensity of the flow increases.

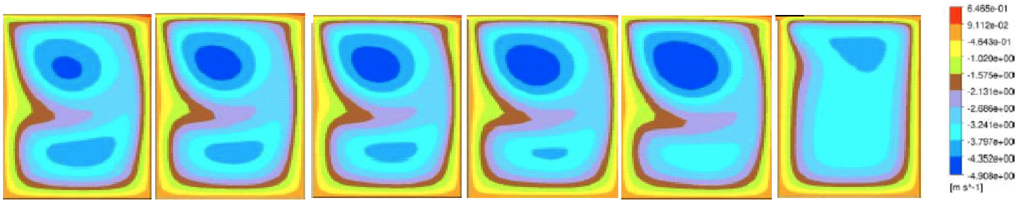
The speed in the stator flute at a constant rotor speed of 750 min^{-1} and a pressure drop between the exit and entrance of the flute of 60 kPa in the cross-sections of the flute is shown in figure 6. This speed is almost uniform centre along the length of the flute (figure 6, f), then two distinct flow areas appear at the top and bottom of the flute (figure 6, a – 6, d). Moreover, the intensity of the upper stream is much higher than of the lower one. The intensity of the upper stream reaches a maximum at the center of the inter-root flute (figure 6, b - 6, d). And the intensity of the lower flow is maximum at the periphery of the knife set (figure 6, a).

The flow rate in the interstitial flute of the stator in figure 7 is almost uniform over the entire length of the flute. Two streams are pronounced in the cross-cut flute of the stator. One stream in the vertical direction is located at the top of the flute closer to the front edge of the garniture knife, the second stream in the downward direction is located at the top of the back edge of the knife.



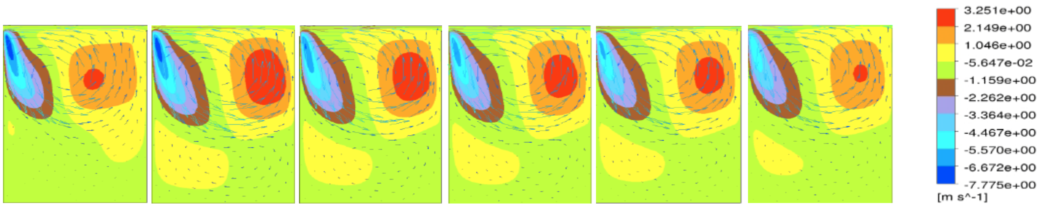
a) b) c)

Figure 5. The flow rate in the interstitial flute of the stator in the middle section of the flute at a speed of 1000 min^{-1} and a pressure drop: a) 60 kPa; b) 80 kPa; c) 100 kPa.



a) b) c) d) e) f)

Figure 6. The flow rate in the interstitial flute of the stator with a rotor speed of 750 min and a pressure drop of 60 kPa in cross sections along the length of the flute: a) 135 mm; b) 105 mm; c) 85 mm; d) 45 mm; e) 25 mm; f) 5 mm.



a) b) c) d) e) f)

Figure 7. The flow rate in the interstitial flute of the stator with a rotation frequency of 750 min^{-1} and a pressure drop of 60 kPa in the vertical direction in sections of the flute: a) 135 mm; b) 105 mm; c) 85 mm; d) 65 mm; e) 45 mm; f) 5 mm.

Both of these flows form a rotating vortex. Moreover, its intensity is maximum in the center of the inter-root flute. The intensity of the hydrodynamic vortex in the rotor is higher than in the stator.

5. Conclusion

The flow rate in the flutes of the rotor depends on the frequency of the rotor rotation. With an increase in the rotational speed from 600 to 1000 min^{-1}, the flow rate increases by 2.3 - 5.4 times, and the speed grows by 2.4-2.6 times. The flow rate and in the stator flute does not depend on the rotational speed. With an increase in the pressure difference between the exit and the entrance of the flute from 60 to 135 kPa, the flow rate in the rotor flutes decreases by 1.4-1.5 times and increases by 2.1-2-2 times in the stator flutes. The flow in the rotor flute is directed from the center to the periphery of the garniture, and in the stator, on the contrary, it is directed from the periphery to the center.

The flow rate in the interstitial flute of the stator with an increase in pressure drop from 60 to 135 MPa increases by 2.3-2.6 times, and at the rotor the flow rate decreases by 1.6-2.7 times. The flow rate of the rotor changes with a change in the angle of the flute to the radius of the garniture. When the angle of inclination is 20 degrees in the direction of the rotor rotation, the flow rate increases by 1.2 times. And at an inclination angle of 20 degrees against the direction of the rotor rotation, the flow velocity decreases by 1.1 times. At the entrance to the cross-breed flute, the flow rate increases sharply, reaches a maximum in the length of the flute of 5-10 mm, then monotonously increases by about 1.2-1.5 times along the flute.

Flow rates and hydrodynamic vortices in the rotor and stator are investigated. The intensity of hydrodynamic vortices in the rotor is higher than in the stator. On the basis of the conducted research, recommendations for the design of the garniture and the operation of knife grinding machines have been developed and implemented. The research results can be used in the design and operation of such machines as centrifugal pumps and compressors.

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