Assessment of the Morphological Properties of Secondary Semi-finished Wood-fibre Products Obtained from Production Waste

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This paper presents the results of an assessment of the morphological characteristics of semi-finished wood-fibre products obtained from waste fibreboard using a rotary cutting machine by dry grinding. The work has established the influence of machine design parameters, such as the gap between the rotor and stator cutters and the angle of the stator cutter contact with the raw materials, on the mass fraction of small fibres and fines in wood-fibre pulp. These parameters determine the main structural characteristics of boards and ensure fibre bonding. The paper describes the collision of single secondary wood fibres that leads to the development of primary cracks, contributing to external and internal fibrillation in the absence of high temperatures and pressure without using chemical additives or water and steam.

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INTRODUCTION

Scientists regard the current state of the biosphere as an acute environmental crisis. The transition to low-waste resource-saving technologies to preserve forests should be the basis for a fundamentally new technological re-equipment of existing wood processing enterprises (Mironov and Mironova 2015).

Krasnoyarsk Krai, located in the central part of Russia, has the largest reserves of forest resources (14.2% of Russia's total forest reserves and 3% of world reserves) and is one of the leaders of wood processing in Russia, occupying a leading position in the timber industry. Moreover, the forest industry's contribution to the region's economy is at most 3%, which is significantly lower than the estimated potential. This is because regional wood suppliers tend to sell unprocessed timber. The "2030 Strategy for the Development of the Timber Industry of the Russian Federation" outlines plans to significantly change this situation by 2030. To achieve this, there is a need to develop such principal areas as pulp and containerboard production, lumber production, board production, furniture and wooden house construction, and equally orient them to the domestic market and for export (Resolution of the Government of the Krasnoyarsk Territory 2018; Government of the Russian Federation 2021; Matygulina *et al*. 2023).

A circular economy, to which it is necessary to strive, means an increase in the possibility of recycling products, reducing the use of new raw materials and demonstrating that a new economy based on the preservation of the environment can help to achieve a minimum-waste production (Zaman 2015).

Currently, global manufacturers of slab materials and paper use a wide variety of raw materials to reduce the consumption of fresh supplies of wood, especially in countries experiencing a shortage of wood (Ihnát *et al*. 2017; Chen *et al*. 2019). There are numerous studies regarding the use of various agricultural raw materials in the production of slab materials (Bower and Stockman 2001), including wheat and rice straw (Halvarsson *et al*. 2010; Norgren 2010), corn and cotton stalks (Abolfazl and Ahmad 2011; Kargarfard and Jahan-Latibari 2011; Theng *et al*. 2017), miscanthus (Klímek *et al*. 2018), sunflower (Bektas *et al*. 2005), processed and unprocessed hay (Pipíška *et al.* 2023), and others.

The processing of secondary semi-finished wood-fibre products is one of the development areas of the wood processing industry in the face of the ever-growing shortage of plant raw materials for business (Nicewicz and Leszek 2010; Wan *et al.* 2014; Şahin 2020; Yano *et al.* 2020).

The largest fibreboard production companies using both dry and wet methods are located in Krasnoyarsk Krai. Such waste, in the form of secondary wood-fibre semi-finished materials, is inevitably generated at different stages of production. This includes processing scrap (10 to 12%), press–ups of the impresfiner - water containing wood (7 to 11%), finished fibreboard waste from panel-sizing machines (3 to 5%), and wastewater fibres (2 to 4%) (Chistova 2010; Morozov 2016). Taken together, these wastes account for 20 to 32% of the total quantity of semi-finished wood-fibre products and represent a serious problem for the environment and economy. In addition, used fibreboard is not put to good use and is practically not recycled. The total quantity of secondary wood-fibre waste becomes significantly higher once these wastes are taken into account.

Analyses carried out at wood processing enterprises in Krasnoyarsk Krai show that the above wastes are either not used at all or are used at less than full capacity. Waste generated from panel-sizing machines is used in wet wood-fibre production. It is soaked, ground in high-speed disk or conical mills, and mixed with press pulp, thereby putting it back into main production. However, studies (Matygulina 2007; Chistova 2010; Zyryanov 2012; Chistova *et al*. 2015) have shown that this leads to the quality of finished products deteriorating: the tensile strength and density of boards decrease, while moisture absorption and swelling in thickness increase. Lump waste is also processed into fuel for thermal power plants (ground to a size suitable for loading into boilers). However, this method is associated with several negative factors: grate sieves are clogged and need to be frequently cleaned, and there are increased atmospheric emissions (combustion releases a large amount of harmful substances such as formaldehyde, phenols, carbon, sulfur dioxide, *etc.*, into the atmosphere). The cost of this fuel is also much higher than that of industrial chips.

Therefore, waste from panel-sizing machines is most often taken to landfills for burial or incineration, which further harms the environment.

Unlike inactivated fibres obtained from longitudinal and transverse cutting wastes, wood particles contained in water (pressed impress fibres) are able to participate in the formation of interfibre and structural bonds. However, most often there is no return to the main production in the technological process. Cork water containing wood is collected in intermediate tanks and exported to local treatment facilities.

Studies show the inefficiency of cutter-type grinding machines for processing inactivated fibres for further use (Chistova 2010; Morozov 2016; Matygulina *et al.* 2021a). It is well known that the defibration method is used to process wood waste in a hydropulper (Petrusheva 2003). Wood waste is pre-ground, soaked to a concentration of 1.5 to 3%, defibrated in a hydropulper to the required fractions, mixed with press pulp (first grinding stage), and transferred to the second stage. The disadvantage of this method is that the resulting fibres can only be used as a filler, because they do not have the required quality characteristics.

The authors (Morozov 2016; Matygulina *et al.* 2021b) have demonstrated the effectiveness of processing secondary wood-fibre waste in an MR-4 grinding machine. The machine operates according to the dry grinding method, in which the fibres are subjected to cutter forces and aerodynamic phenomena occurring in the grinding chamber. Despite the fact that the fibres show signs of hornification, they also have main cracks, and external and internal fibrillation is clearly visible, which increases the specific surface area of wood-fibre pulp and promotes the formation of cohesive bonds in the finished boards.

This paper considers the preparation of wood-fibre waste, with further assessment of the dimensional, qualitative, and morphological characteristics of wood fibre. The authors' theoretical and experimental studies revealed quantitative dependencies of the dimensional, qualitative, and morphological characteristics of wood fibre prepared by the dry grinding method on the process and design parameters of grinding machines.

EXPERIMENTAL

Materials

Waste generated from dry and wet wood-fibre production, including process scrap and longitudinal and transverse wastes obtained from panel-sizing machines, was used as a raw material for experimental studies. The raw materials were taken from existing fibreboard enterprises (wet-process method at AO Lesosibirsky Lesopilno-Derevoobrabatyvayuschiy Kombinat No. 1 (Lesosibirsky Woodworking Plant No. 1), dry process method at AO Novoeniseysky Lesokhimichesky Kompleks (Novoeniseysky Timber and Chemical Complex) that are part of SEGEZHA GROUP). Figure 1 shows the types of raw materials used in the study.

Fig. 1. Types of raw materials used in the study

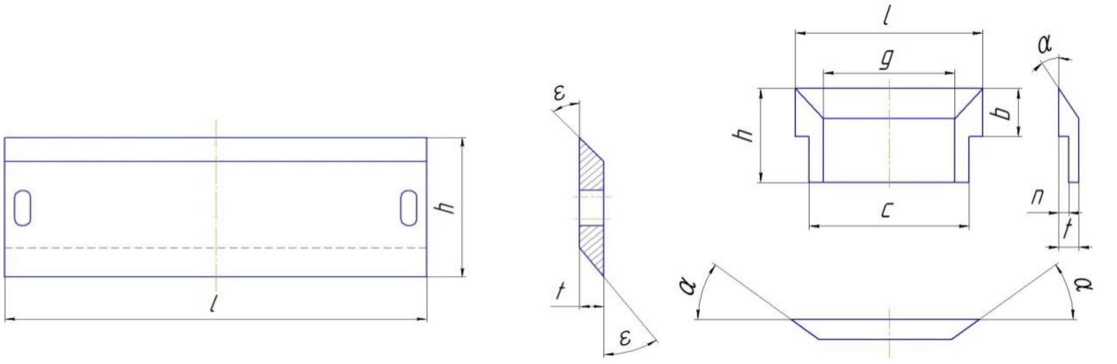
Wet-process fibreboard (Interstate Standard No. 4598, 2018) is manufactured without using bonding agents because the raw material is mainly coniferous wood, and only an aqueous solution of sulfuric acid and a paraffin emulsion are present as additives. In the production of dry-process fibreboards, carbamide-formaldehyde resin (KF–MT–15, Himtech, Moscow, Russian Federation), sulfuric acid (Angarsk Nitrogen-tuk Plant, Angarsk, Russian Federation), paraffin emulsion (Yaroslavl Plant of Paraffin Products, Yaroslavl, Russian Federation), ammonium chloride (Chempack, Moscow, Russian Federation), and carbamide (grade A, URALCHEM, Perm, Russian Federation) were added to wood fibres in quantities specified under the interstate standard (EN 622-5 2009).

Molding compound composition for fibreboard production is present in the authors' previous work (Matygulina *et al.* 2021).

Methods

Wood-fibre waste generated from the production methods listed above was defibrated using an MR-4 rotary cutting machine at the Scientific and Technical Laboratory of the Department of Machines and Devices of Industrial Technologies of M. F. Reshetnev Siberian State University of Science and Technologies (Krasnoyarsk, Russian Federation).

The configuration, specifications, operating principle, and sequence of the MR-4 rotary cutting machine are set out in previous studies (Morozov 2016; Matygulina *et al.* 2021a,b). Unlike the traditional method of grinding wood-fibre semi-finished materials, this machine does not use water, pressure, steam, or high temperature. This rotary cutting machine can operate in both continuous and periodic mode. Figure 2 shows the configuration of rotor and stator grinding cutters used in the experiment. This configuration was developed based on the results of numerous preliminary tests (Chistova *et al.* 2018a,b).



a **b**

a: is the cutting anvil, b: is the rotor cutter

Fig. 2. General view of the grinding cutters (*α* is the sharpening angle, °; *h* is the cutter height, mm; *l* is the cutting edge length, mm; *g* is the cutter length, mm; *t* is the cutter thickness, mm; *b* is the groove height, mm; *n* is the groove depth, mm; *c* is the cutter base length, mm)

The stator cutter is rectangular in shape with bevel angles ε = 40° and 35°, length *l* = 212 mm, thickness *t* = 12 mm, height *h* = 82 mm. The rotor grinding cutters are T-shaped with three cutting edges and bevel angles α = 34°, thickness *t* = 10 mm, height *h* = 47 mm, one cutting edge *l* = 94 mm in length, and two cutting edges on the sides of the cutter *b* = 46 mm in size.

Numerous theoretical and experimental studies show that such factors as the gap between the rotor and stator cutters and the angle of the stator cutter contact with the raw material have the greatest effect on the grinding process under consideration. Such factors as the temperature of the wood-fibre pulp, the ratio of coniferous and deciduous species and the rotor rotation frequency have less effect (Chistova 2010; Zyryanov 2012; Morozov 2016; Vititnev 2019).

To assess the effectiveness of the preparation of secondary wood-fibre semi-finished materials, the dimensional, qualitative, and morphological characteristics of secondary wood fibres were evaluated: fractional quality index, fibre-length-to-diameter ratio, specific surface area of fibres, mass fraction of fine fibres, Group A fibrilplasms, and Group B mehlstoff in the total mass.

The experimental results related to the influence of technological and design parameters of the MR-4 rotary cutting machine on the dimensional and qualitative parameters of wood fibres are presented in Matygulina *et al.* (2021b).

The morphological assessment of fibres is also an important indicator of the quality of ground wood-fibre pulp. They were evaluated on a HITACHI TM4000Plus electron microscope (Westford, MA, USA). A 0.1 g mass of wood-fibre pulp (absolute dry matter) was evenly distributed on a microscope slide. The resulting image was evaluated using the ScopePhote program. Then, mathematical calculations in the Microsoft Office Excel package (Microsoft Corp., Redmond, WA, USA) and data presented in Table 1 were used to determine secondary wood fibre groups.

The percentage of each fibre group in the total mass was determined according to Eq. 1,

$$X = \frac{m_g}{m_s} \cdot 100 \tag{1}$$

where m_g is the mass of (large, medium, small) fraction fibres, g; m_s in the total sample mass, g.

One of the most important indicators of the quality of fibrous semi-finished products is the fibre-length-to-diameter ratio (*L*/*D*). The ratio characterizes the intensity of changes in the geometric dimensions of wood fibres in different directions and determines their specific surface area and flexibility. The method for determining the arithmetic mean values of fibre length *L* and diameter *D* is presented in earlier studies (Zyryanov 2012; Matygulina *et al.* 2021b).

Table 1. Morphological Characteristics of Various Wood Fibre Fractions

Indicator	Fibre						
	Large	Medium	Small	Fines			
				Fibrilplasm		Mehlstoff	
				A	B	A	B
Length (*L*) (mm)	More than 4	4 to 1.5	1.5 to 0.2	0.2 to 0.3	0.04 to 0.09	From 0.04	0.15 to 0.2
Diameter (*D*) (mm)	More than 0.5	0.1 to 0.05	0.05 to 0.02	From 0.003 and above		0.01 to 0.02	0.01 to 0.003
L/D	10 to 20	35 to 50	10 to 15	65 to 100	15 to 30	10 to 15	35 to 55

The authors carried out a two-factor experiment according to the second-order B-plan with processing in the STATISTICA-6 software package (Dell Technologies, version 6.1, Round Rock, TX, USA) using the Quasi-Newton method (Borovikov and Borovikov 1998; Pizhurin and Pizhurin 2005). Table 2 shows the input and output experimental parameters and the intervals of their variation. The WPF and DPF indices were used to specify the types of fibreboard used (both wet and dry methods).

Table 2. Input and Output Experimental Parameters, Levels and Intervals of their Variation

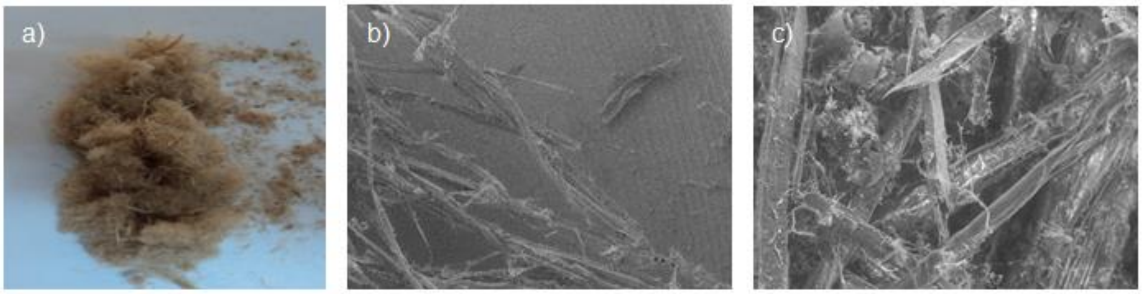
Parameter	Designation	Variation Interval	Variation Level		
			-1	0	+1
Input parameters (controllable factors)					
Wet-process fibreboard					
Gap between the rotor and stator cutters (mm)	z_{WPF}	3	3	6	9
Angle of the stator cutter contact with raw material (°)	ε_{WPF}	45	135	180	225
Dry-process fibreboard					
Gap between the rotor and stator cutters (mm)	z_{DPF}	3	2	5	8
Angle of the stator cutter contact with raw material (°)	ε_{DPF}	45	135	180	225
Output parameters (controllable factors)					
Wet-process fibreboard	Dry-process fibreboard				
Mass fraction in the total mass (%):	Mass fraction in the total mass (%):				
- fine fibres B_{MWPF}	- fine fibres B_{MDPF}				
- Group A fibrilplasms $F_{(A)WPF}$	- Group A fibrilplasms $F_{(A)DPF}$				
- Group B mehlstoff $M_{(B)WPF}$	- Group B mehlstoff $M_{(B)DPF}$				

The experiment was performed according to the following scheme: the values of the gap between the rotor and stator cutters were set at a certain level (specified in Table 2) and the angles of feeding the raw material into the grinding chamber were changed by adjusting the cutting anvil. Thereafter, the values of the angle of inclination were set, with the value of the gap between the cutters remaining unchanged.

RESULTS AND DISCUSSION

The wood-fibre pulp contained large, medium, and small fibre fractions and fines. This paper presents the results of research on only fine fibres and fines, which determine the main structural characteristics of boards, taking into account the use of secondary wood fibres. In turn, fines contain Group A and B fibrilplasms, as well as Group A and B mehlstoff. Studies show that fines account for 35 to 40% of the total mass of secondary wood fibres (Zyryanov 2012; Morozov 2016).

Group B fibrilplasm and Group A mehlstoff particles serve as a filler and are located between the reinforcing fibres. The particles make it difficult for the firbres to converge during mat creation and are poorly involved in the formation of adhesive and cohesive inter-fibre bonds. Contrastingly, the active nonfibrous components and the finely dispersed fibre fractions (Group A fibrilplasm and Group B mehlstoff) form cohesive bonds with large, medium, and small fibres and with each other, thereby increasing the specific contact surface in the boards. This results in the formation of additional cohesive bonds having the structure "fibre – finely dispersed fibre fraction – fibre". Figure 3 shows wood fibres treated in an dry grinding environment using the MR-4 rotary cutting machine.



Appearance of the fiber 1000 times magnification 2500 times magnification

Fig. 3. Secondary wood fibres treated in a dry grinding environment using the MR-4 rotary cutting machine

The following are the experimental results represented as mathematical equations (2 through 7) with natural factor values describing wood-fibre waste preparation. All the equations were tested for adequacy using Fisher’s F-test. The significance of the coefficients was evaluated using the Student's t-test. The confidence probability was 95 to 99%. The approximation coefficient confidence (R^2) was close to one (Borovikov and Borovikov 1998; Pizhurin and Pizhurin 2005). The equations obtained are as follows:

– Fine fibre fraction (%):

$$B_{MWPF} = 61.51–0.7·z_{WPF}+2\ ε_{WPF}+0.07·z_{WPF}^2–0.9·ε_{WPF}^2+0.03·z_{WPF}·ε_{WPF} \tag{2}$$

$$B_{MDPF} = 67–1.6·z_{DPF}+1.7·ε_{DPF}–0.2·z_{DPF2}–0.13·ε_{DPF}^2+0.01·z_{DPF}·ε_{DPF} \tag{3}$$

– Group A fibrilplasm (%):

$$F_{(A)\ WPF} = 14.3+0,07·z_{WPF}–1.5·ε_{WPF}–0.03·z_{WPF}^2+0.1·ε_{WPF}^2+0.01·z_{WPF}·ε_{WPF} \tag{4}$$

$$F_{(A)\ DPF} = 11.1+1.3·z_{DPF}–2.4·ε_{DPF}–0.2·z_{DPF}^2+0.2·ε_{DPF}^2–0.01·z_{DPF}·ε_{DPF} \tag{5}$$

– Group B mehlstoff (%)*:*

$$M_{(B)\ WPF} = 7.5+0.6·z_{WPF}+0.5·ε_{WPF} –0.03·z_{WPF}^2–0.01·ε_{WPF}^2–0.1·z_{WPF}·ε_{WPF} \tag{6}$$

$$M_{(B)\ DPF} = 11.4+1.4·z_{DPF}–3.1·ε_{DPF}–0.2·z_{DPF}^2+0.3·ε_{DPF}^2–0.01·z_{DPF}·ε_{DPF} \tag{7}$$

Figures 4a and 4b show the graphical dependencies based on the models with natural factor values.

Analysis of Eqs. 2, 4 and 6 and graphical dependencies (Fig. 4) show that the percentage of fine fibres in the total mass with an increase in the gap between the rotor and stator cutters z from 3 to 5 mm reached its minimum values of 62.5 to 63% to absolute dry matter. The same happened when the angle of the stator cutter contact with the raw material was changed from 180 to 200°.

With a change in the size of the gap between the rotor and stator cutters z = 3 to 6 mm and the angle of the stator cutter contact with the raw material $ε$ = 170 to 200°, the percentage of Group A fibrilplasm in the total mass of the semi-finished wood-fibre product reached its maximum value of 12.5 to 12.7% to absolute dry matter, Group B mehlstoff – 11.9 to 12.2% to absolute dry matter. A further increase in the gap up to 2 mm and from 6 mm and the angle up to 160° and from 210° led to a decrease in the percentage of the semi-finished wood-fibre product of these fine groups in the total mass.

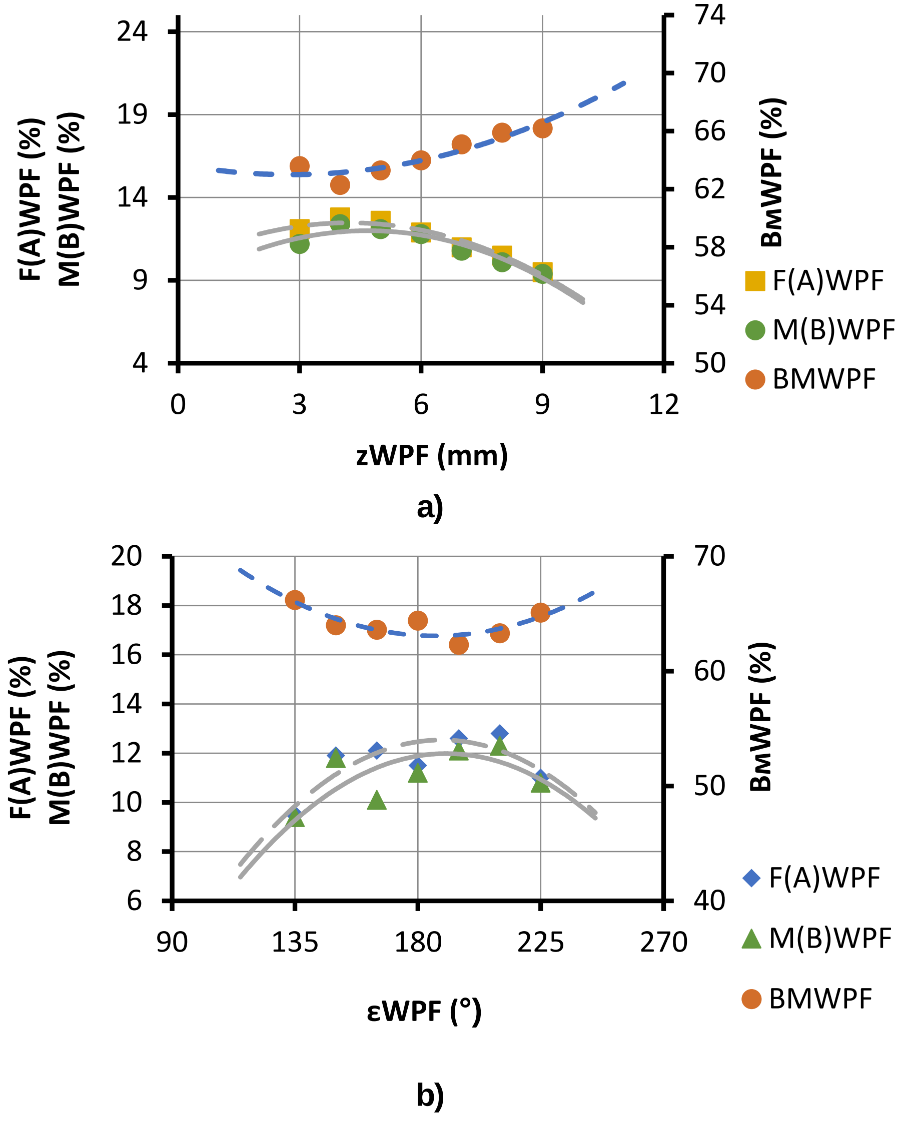


Fig. 4. Dependencies of the morphological characteristics of secondary wood fibres on the process and design parameters of the rotary cutting machine (wet-process fibreboard production)

Next, the authors constructed graphical dependencies reflecting the influence of the grinding parameters on properties of fibrous pulp of the semi-finished wood-fibre products obtained by dry wood-fibre production (Fig. 5).

From Eq. 3 and the graphical dependencies presented in Fig. 5a, it can be seen that the percentage of fine fibres in the total mass increased with an increase in the gap between the rotor and stator cutters and decreased with an increase in the angle of the stator cutter contact with the raw material. It reached its minimum values of 67 to 69% at $z \approx 2$ to 4 mm and $\varepsilon \approx 190$ to 225°. Figures 5 a and b also show the graphical dependencies of the content of the Group A fibrilplasm and Group B mehlstoff on the process parameters of the grinding machine. The graphical dependencies show that with a decrease in the gap between the rotor and stator cutters and the angle of the stator cutter contact with the raw material, the percentage of A fibrilplasm and B mehlstoff increases and reaches its maximum value of 7 to 8% at $z \approx 2$ to 5 mm and $\varepsilon \approx 200$ to 225°.

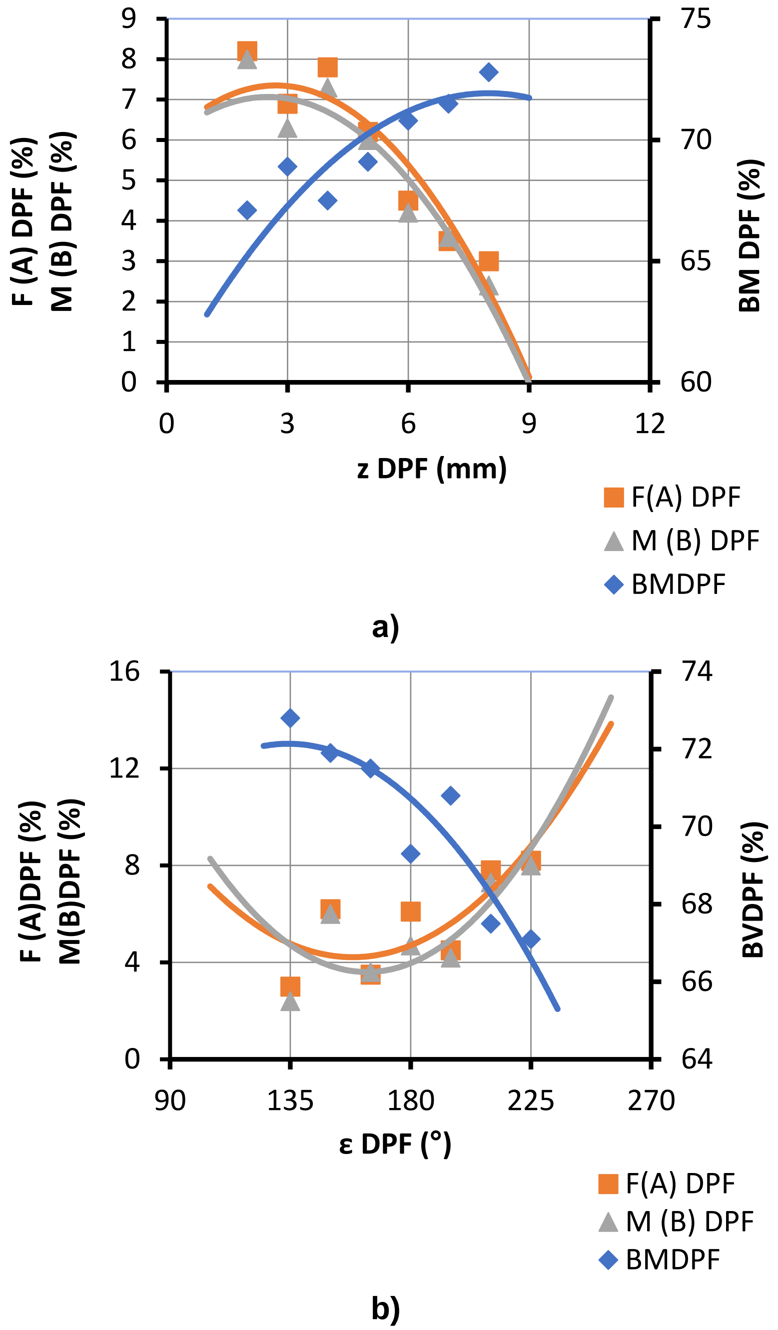


Fig. 5. Dependencies of the morphological characteristics of secondary wood fibres on the process and design parameters of the rotary cutting machine (dry-process fibreboard production)

Therefore, it can be noted that with a decrease in the percentage of fine fibres in the total mass, the percentage of A fibrilplasm and B mehlstoff increased. This can be explained by the fact that the variation of input parameters results in a flow trajectory that fully contributes to the collision of wood fibres and, consequently, to an increase in their specific surface area.

Processing in panel-sizing machines is followed by cutting, compression, and friction forces during wood-fibre waste defibration. This leads to the following types of wood fibre damage: transverse breakage, fibre end brooming, and local removal of individual sections of the primary and outer secondary wall layers. The waste fibres obtained from wet wood-fibre production include in which the layering of the inner layers is visible, internal and external fibrillation, and flattened fibres taking the shape of flat ribbons. This external and internal fibrillation of wood fibres contributes to an increase in the specific surface area of the wood mat and to bonding in boards.

Visual observations were made to describe the flow trajectories inside the grinding chamber. Air flows with wood fibres move randomly, changing their direction and density depending on the geometry of the grinding tool. In the MR-4 rotary cutting machine chamber, the flow trajectory approaches turbulence under steady-state conditions (this is schematically shown in Fig. 6).

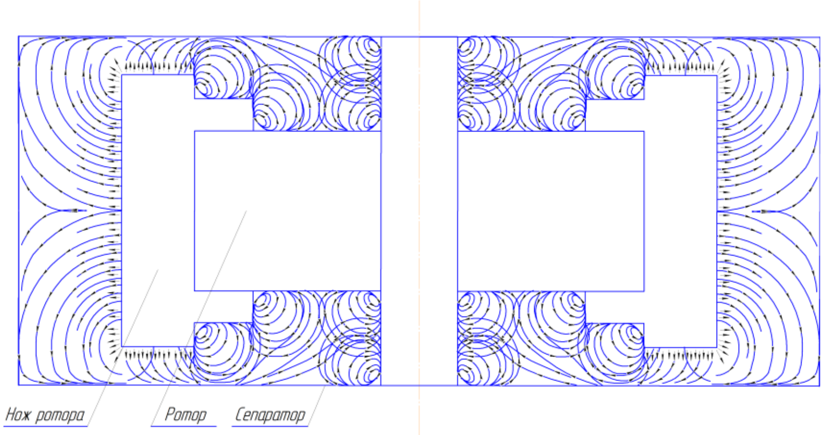


Fig. 6. Movement of small wood fibres in the turbulent flows of the MR-4 grinding chamber

To describe the motion of these flows, a description of the turbulent motion of a continuous incompressible Newtonian single-phase fluid by numerical simulation (Minibaeva *et al*. 2018) was proposed. The mathematical solution to this process will be a differential equation of conservation of mass (continuity equation) and transfer of momentum (Reynolds equation) in partial derivatives in cylindrical coordinates. Equation 9 is as follows,

$$\rho\left(v_r\frac{\partial v_z}{\partial r}+\frac{v_k}{r}\frac{\partial v_z}{\partial k}+v_z\frac{\partial v_z}{\partial r}\right)=-\frac{\partial P}{\partial z}+\rho g_z+\mu\left(\frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial v_z}{\partial r}\right)+\frac{1}{r^2}\frac{\partial^2 v_z}{\partial k^2}+\frac{\partial^2 v_k}{\partial z^2}\right) \qquad (8)$$

$$\mu=\mu_{м}+\mu_{m}, \qquad (9)$$

where $v_r, v_k,$ and v_z are the radial, tangential, and axial components of the velocity, respectively (m/s); $r,\ k,$ and z are the distance in the radial, tangential, and axial directions, respectively (m); $\mu_{\text{М}}, \mu_{\text{Т}}$ are the dynamic coefficients of molecular and turbulent viscosity, respectively; P is the pressure (Pa); ρ is the air density (kg/m^3); and $g_r, g_k,$ and g_z are the components of the acceleration vector in radial, tangential, and axial directions, respectively.

The complex nature of the movement of air flows with wood fibres at high speed forms vortex flows and circulation zones in the second zone of the grinding machine. This results in the defibration of wood-fibre waste over a certain period of time. The denser movement is concentrated along the edges and in the grooves of the grinding rotor cutters.

In the corners, the movement of airflow spreads along an irregular-shaped ellipsoid closed trajectory and the conditional radii of these ellipsoids will increase, depending on the removal of the fibre movement in the flow from the structural elements of the working parts of the rotor cutter (groove, protrusion). The movement trajectories of wood fibres along the spirals of an irregular ellipse inevitably overlap with each other. With that, wood fibres collide, various stresses occur and accumulate, which results in the development of primary cracks in the fibres. There is internal and external fibrillation that contributes to an increase in the specific surface area of the fibres, despite the fact that signs of hornification are present there.

The trajectory of secondary wood fibres in the grinding chamber of a rotary cutting mill can be considered by assuming the theoretical aspects of the movement of a one-dimensional airflow and a flow around wood fibre bodies with an incoming flow. The geometric location of the points at which single wood fibres are in motion will be called the fibre trajectory. The velocity vector of this fibre at all points of the trajectory is directed tangentially with respect to it.

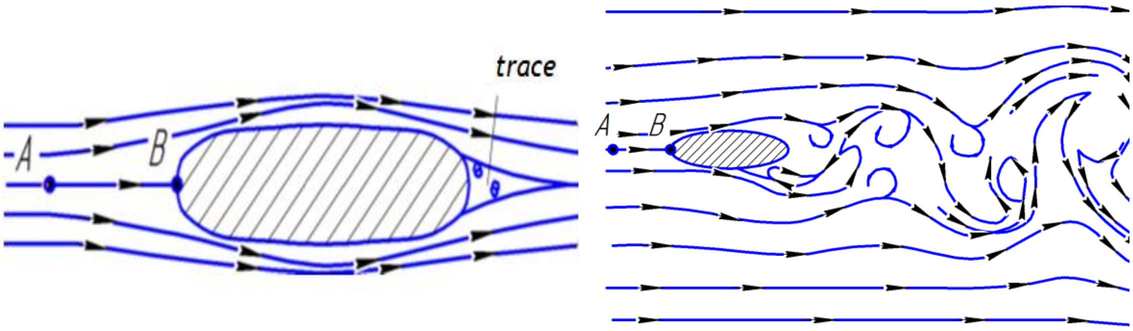
For low flow velocities (at $M < 0.3$), it is assumed for simplicity that the air is incompressible, *i.e.*, the air density does not change from section to section ($\rho = const$). Thus,

$$V_1 F_1 = V_2 F_2 \tag{10}$$

where V_1, V_2 are the air velocities in the filament section, m/s; F_1, F_2 are the filament cross-sectional areas, m^2.

Therefore, when the cross-sectional area of a wood fibre or a wood fibre bundle decreases, the air flow velocity in the stream increases, and *vice versa*. This is true for the conditions ($M < 1$) of defibration in the rotary cutting machine between the rotor and stator cutters, because perturbations propagate at a speed greater than the flow velocity and can be distributed in different directions in the machine chamber. Thus, if a subsonic flow is in a solid body, then perturbations propagate throughout the flow, and the entire flow will rearrange; the air particle somehow prepares for a flow around.

When there is an unlimited airflow around wood fibres in the initial sections, the influence of viscosity and turbulence is concentrated near the flow around solid surfaces. Figure 7 (a, b) shows the flow around a single small- and large-fraction wood fibre with an incoming flow.



a) fine-fraction fibre **b)** large-fraction fibre

Fig. 7. Flow around a single wood fibre with an incoming flow

When there is an incoming airflow around a single fine-fraction wood fibre (Fig. 7a), its end has a critical point *B* where the flow velocity is zero due to complete braking. The dynamic component at this point is zero, while the static pressure is maximum and equal to the full pressure. At any other point on the surface of the body, the flow velocity will be greater than zero, then the static pressure will be less than at the critical point.

Figure 7b shows that airflow around large wood fibres and fibre bundles is accompanied by the development of a Kármán vortex street consisting of multi-scale vortices carried away in a turbulent flow. The authors are convinced that vortex generation leads to the formation of a low-pressure area behind a wood fibre bundle. This area forces small wood fibres (pulp) into these vortex flows, where they collide.

When the air flow hits the secondary wood fibre when it is moving in the grinding chamber along the stream line branching off on the solid surface at point *A*, elementary air volumes decrease their velocity (slow down) from the values v at point *B* to zero at point *A*; as such, for stream line *AB*, Bernoulli's equation can be represented as follows (Mohirev *et al*. 2019),

$$\frac{v^2}{2}+\frac{k}{k-1}\frac{p}{\rho}=\frac{k}{k-1}\frac{p_0}{\rho_0} \tag{11}$$

$$\frac{v^2}{2}+\mathrm{c_p}T=\mathrm{c_p}T_0 \tag{12}$$

$$\frac{v^2}{2}+\frac{\mathrm{a}^2}{k-1}=\frac{\mathrm{a}_0^2}{k-1} \tag{13}$$

where v is the air flow velocity (m/s); $p_{\mathrm{c},}\ p_{\mathrm{c0}}$ is the air pressure at a point (Pa); ρ, ρ_0 is the air density at a point (kg/ cm^3); T is the absolute air temperature at a point (°C); a is the speed of sound at a point (m/s); c_{p} is the specific heat capacity of air, J/(kg·K); and k is the coefficient for air, $k = 1.4$.

Values p, ρ, T and a at the point of stream lines *B* where $v = 0$ are called braking parameters, and this point itself is a braking point.

According to Bernoulli's equation, as the flow velocity increases, the dynamic pressure will increase, and the static pressure, respectively, will decrease, because their sum should remain unchanged. These conditions ensure that the wood fibre moves in the airflow.

For wood fibres, with an increase in the Reynolds number, the growth rate of the airflow separation zone largely depends on the fibre-diameter-to-length ratio. A disruption of the laminar body flow around pattern during defibration will ensure changes in the dimensional and qualitative characteristics of secondary wood fibres. Further experimental studies of this phenomenon are necessary to understand the scenario of laminar flow disruption to turbulent flow around the fibres.

CONCLUSIONS

1. Based on the foregoing, the authors’ assumptions that changes in the flow velocity and direction will affect the energy released during collisions of single wood fibres are confirmed.
2. The effect of the defibration of wood-fibre waste obtained from panel-sizing machines by dry grinding on the dimensional and qualitative characteristics of secondary wood fibres appears to take place due to the collision of secondary wood fibres in the machine

grinding chamber. The collisions of single secondary wood fibres allow obtaining primary cracks and promote the formation of external and internal fibrillation in the absence of high temperatures and pressure, without chemical additives, and without using water or steam.

3. Studies have shown that the qualitative characteristics of finished fibreboard directly depend on the predominance of Group A fibrilplasm and Group B mehlstoff in the ground mass. This can be explained by the fact that Group A fibrilplasm and Group B mehlstoff fines have the largest length and the smallest diameter compared to other fine groups. These indicators characterise fibres and contribute to bonding in finished boards.
4. Therefore, the above theoretical studies and evaluation of the experimental results confirm the effectiveness of the preparation of wood-fibre waste obtained from panel-sizing machines in air, while the optimisation of technological processes in the preparation of wood-fibre wastes by dry grinding is an important field that requires further research.

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