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SIMULATION OF TRANSLATIONAL - ROTATIONAL MOTION OF WOOD PARTICLES DURING THE PROCESS OF PARTICLE ORIENTATION

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Abstract:
The simulation from the motion of flat particle revealed that the fall depends on the height of the drop, the thickness and density of the particles and does not depend on its length and width. The drop in air is about 20% longer than in vacuum.

During orientation from angular particles the velocity of rotating particles with a length of 150mm is reduced by 18%, for particles with a length of 75mm by 12%. This reduction increases linearly with decreasing density of particles.

A velocity field acting on the particle in the fall and rotation was presented. The results of the study prove the possibility to reduce the scatter of the particles during the mat's formation, that in turns can increase the board's bending strength.

Key words: *OSB; flat particle; simulation; fall time; rotational torque; drag coefficient.*

INTRODUCTION

According to the modern technology of oriented strand board (OSB) and laminated strand lumber (LSL) manufacturing, wood particles should be oriented during the formation of mat of wood strand before the heated pressing process. Placing the particles in the external layers of mat in the longitudinal direction (transport direction from the mat) and in the middle layer – in transverse direction it is possible to achieve a significant increase in the flexural strength of manufactured panels (Track 1984, Chen 2008). The MOE depends from the particle orientation (Sharma 1993) and their shape and geometrical dimensions (Kruse 2000). Moreover, the smaller the angle of dispersion of the particles, the greater the strength of the board. Orientation of wood particles is one of the basic operations in the process of OSB manufacturing. So the aim of this study is to describe a model for the particle orientation.

METHOD

Knowing the dynamics of the wood particles, especially the change of speed and time of the particles fall and turn from the orienting process to the forming of mat of wood strand, it is possible to find the rotational torque so that each particle would be placed into the layer with the smallest possible deviation angle. As the result the static bending strength of OSB could be significantly improved.

It is important to analyze the translational and rotational motions of the particles separately.

Except rotational motion, only gravity $m \cdot g$ and air drag F_L can influence a freely falling particle in the air. The differential equation (eq. 1) of the translational motion of a particle is the following:

$$m\frac{d^2s}{dt^2} = m \cdot g - F_L, \qquad (1)$$

m – particle mass, kg;
s – distance passed by a particle, m;
g = 9,81m/s^2 – acceleration of free fall.

With the strength F_L depending on the velocity of the particles relative to the drag equation (1) is the following:

$$m\frac{d^2s}{dt^2} = m \cdot g - C_x \cdot S_d \cdot \rho_{в}\frac{V^2}{2}, \qquad (2)$$

C_x – drag coefficient of a particle;
S_d – cross-sectional square of the projection of a particle on the board perpendicular to the direction of its motion, m^2;

ρ_L = 1.29kg/m^3 – density of air under normal conditions;
V – translational velocity in the particle fall, m/s.

Mass of a particle depends on its size and specific gravity of the material:

$$m = B \cdot L \cdot H \cdot \rho_M, \qquad (3)$$

B – width of a particle, m;
L – length of a particle, m;
H – thickness of a particle, m;
ρ_M – density of the particle (400-700)kg/m^3.

Square *Sd* in plane-falling of a particle is determined by the formula:

$$S_d = B \cdot L$$

To determine the velocity V by the equation (2) it is necessary to know the value of the air drag coefficient *Cx*. Values of C_x at small Reynolds number *Re* range published in different scientific works are too variable and unreliable because they are based on insufficient number of experiments. Coefficient C_x depends nonlinearly on the number of *Re*, and *Re* depends on the particle velocity *V*. Due to the aerodynamic modeling of processes occurring during the fall of the particles in the air, it is possible to exclude values of C_x from the calculations.

To calculate the fall of a particle depending on its aerodynamics, the modeling of the braking force depending on the fall time of a particle F_L was carried out with the help of Comsol Multiphysics 3.5 program (Roger 2012). The resulting value of the force F_L in the form of approximating equation was introduced into the S-model of particle fall created by MatLab / Simulink. The speed and the fall of the particle were calculated including the air drag. This eliminates the need to use non-linear dependence of the C_x on the Reynolds number.

As the result the velocity field around a steadily moving particle was found. For example, Fig. 1 shows a picture of the particle stream (excluding rotation) in 0,2 seconds after the start of movement.

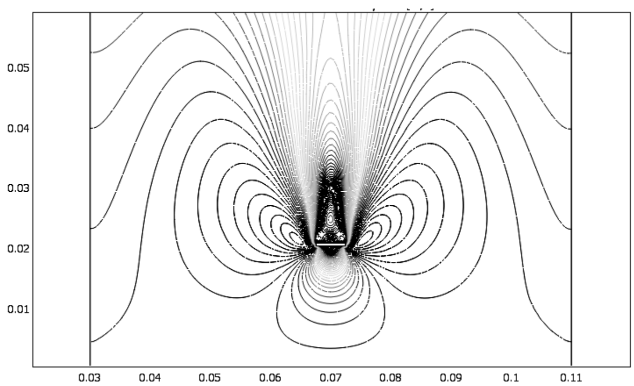

Fig. 1.
The velocity field in 0.2 s after the start of the fall.

The dependence of the air drag F_L on the Reynolds number approximating by using a package of Curve Fitting program MatLab was proved by modeling. The equation (correlation coefficient R = 0,99991) is the following:

$$F_{\text{æ}} = \frac{B \cdot L}{B_0 L_0}\left(0.0007845 \cdot Re^2 + 0.0001813 \cdot Re + 4.05 \cdot 10^{-5}\right), \qquad (4)$$

B_0 = 0,02m – average width of a particle;
L_0 = 0,1m – average length of a particle.

A simulation model for this task was developed by Simulink package. Equation (4) in the model calculates the block Fcn2. Circuit model is shown in Fig. 2, some simulation results - in Fig. 3.

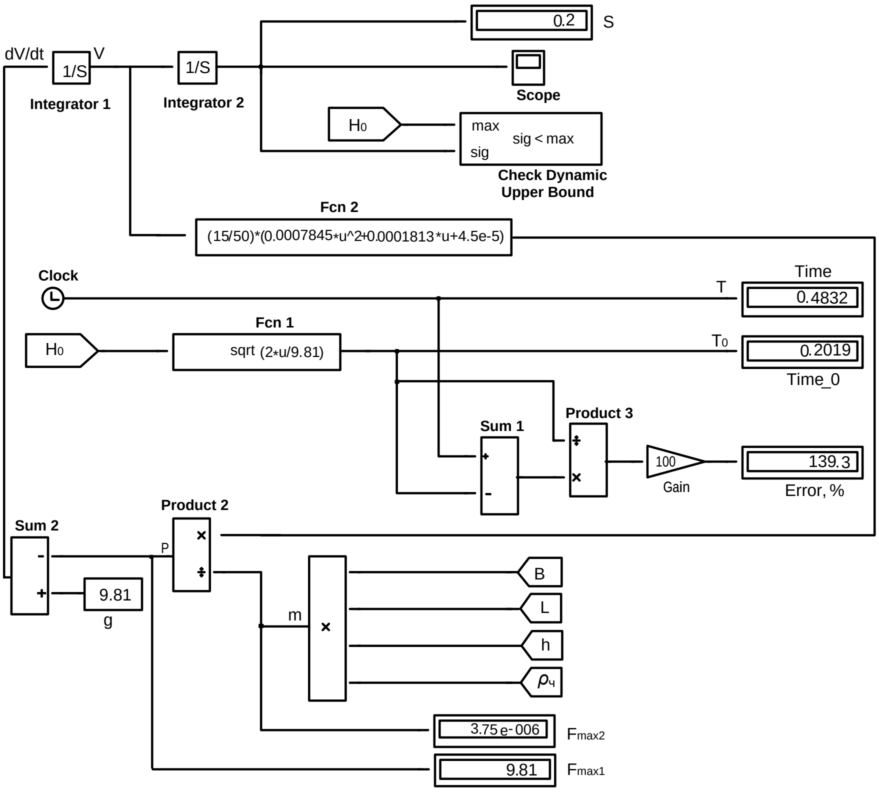

Fig. 2.
Simulation model (S-model) of the fall of a flat particle.

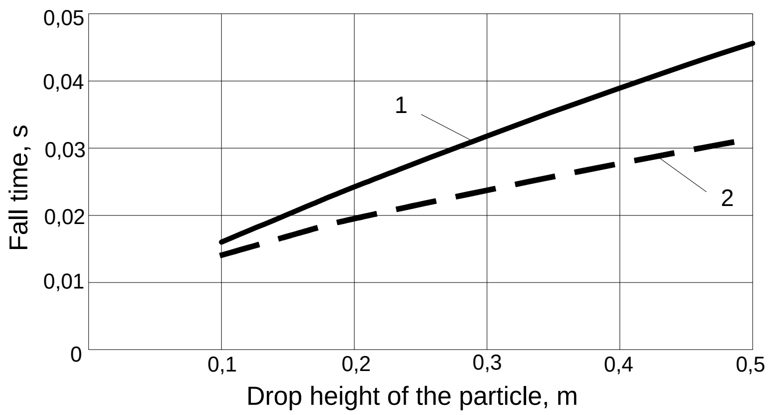

Fig. 3.
The dependence of the fall time of a particle on the height of the fall H_0 for $B = 0,02m$; $L = 0,1m$; $H = 0,0005m$; $\rho_M = 400kg/m^3$: 1 - for the air, 2 - for the vacuum.

The simulation showed that the fall of a particle T_0 depends on its thickness and density and does not depend on its length and width as with the increase of these values the sectional area of the particle also increases, therefore the air drag growths as well.

Knowing the fall time of a particle T_0, it is possible to calculate the speed of its rotation [rad/s] required to minimize the angle of a particle in the mat of wood strand:

$$\omega_0 = k \cdot \frac{2\pi n + \alpha_{in}}{T_0}, \qquad (5)$$

a_{in} – angle of descent of the particles from the guide, depending on the distance between the guides and the length of a particle [rad];
n = 0 or 1 – the number of revolutions;
k – air drag coefficient including the slowing of the particle rotation.

Factor n is determined by the productivity of the orienting device. The quicker orientation of the particles is required, the greater rotational torque should be given to them and the greater the initial velocity ω_0 should be. A particle can perform an additional turnover. In this case the angle of particles spread in the mat of wood strand increases. The optimal speed rail system in the orientation of wood particles (Plotnikov 2008) can be calculated from (5).

To analyze the air drag coefficient k in (5) it is necessary to analyze the rotational motion of a particle. In this model a particle with the length L, the width B and the thickness H is rotating around the axis OO^I with angular velocity ω (Fig. 4).

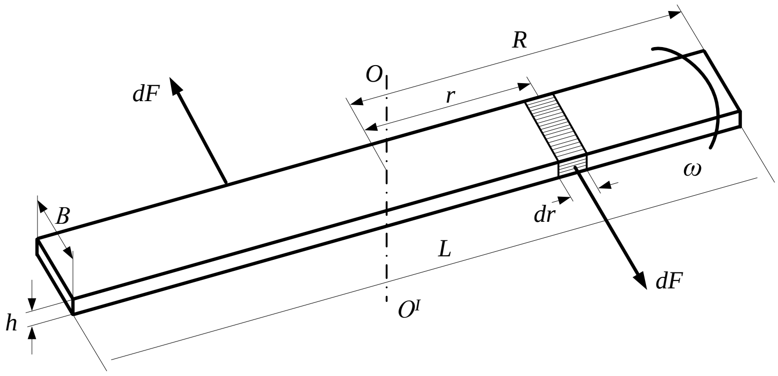

Fig. 4.
Free rotation of a rectangular particle in the air.

Fig. 4 shows: $R = L/2$; dF - elementary force of resistance; ω - speed of rotation particles; r - the current coordinates of the section of the particle.

Air drag F varies in different parts of a particle as its different parts move with different linear velocity relative to the air. As the example, an infinitesimal part of the particle with the length at a distance r from rotation axis OO^I was analyzed. In this case the elementary resistance influencing the particle with the length dr and the width B is determined as follows:

$$dF = Cx \cdot \rho_M \cdot B \cdot dr \cdot \frac{V_\kappa^2}{2}$$

V_κ – linear velocity of the edges of the particle, m/s.

With the linear velocity shown through the angular velocity $V_\kappa = r \cdot \omega$ the equation is the following:

$$dF = Cx \cdot \rho_L \cdot B \cdot dr \cdot \frac{\omega^2 r^2}{2}, \qquad (6)$$

Elementary braking torque with the force influencing the second half of the particle is:

$$dM = 2dF \cdot r = C_x \cdot \rho_L \cdot B \cdot \omega^2 \cdot r^3 \cdot dr, \qquad (7)$$

To determine the total braking torque it is necessary to integrate (7) over the length of the particle from the axis of rotation to the end:

$$M = \int_0^R dM = \int_0^R Cx \cdot \rho_L B \cdot \omega^2 \cdot r^3 \cdot dr = \rho_L B \cdot \omega^2 \int_0^R Cx \cdot r^3 \cdot dr = K \int_0^R Cx \cdot r^3 \cdot dr, \qquad (8)$$

$$K = \rho_L \cdot B \cdot \omega^2$$

Air drag coefficient C_x in (8) depends on the velocity of the particles relative to the air. The velocity is determined by the current coordinates of the section and the angular velocity ω. To summarize the results, the coefficient C_x was supposed to be the following:

$$Cx = A + \frac{\upsilon}{\sqrt{V}} = A + \frac{\upsilon}{\sqrt{\omega r}} = A + \frac{\upsilon}{\sqrt{\omega}\sqrt{r}}, \qquad (9)$$

An important feature for the motion of particles in the orientation device is the laminar air stream around the particles. The size of the particles used to manufacture the OSB are up to 150mm, with width 30mm, thickness 1mm (Thoemen 2010) and rotational motion speeds ranging from 1 to 8rad/s, resulting in a

Re from 10 to 800 characterizing the stream around the particles. This range corresponds with a laminar regime. Laminar motion of homogeneous media and their interaction with streamlined objects falls under the numerical methods of calculation; so to determine the coefficient C_x, a numerical experiment was carried out. It consisted of the following steps:

- using Comsol Multiphysics 3.5, a stationary process of a particle in the air stream was calculated. The calculation showed that it is determined by the total force influencing the rigid object;
- according to the results, the air drag coefficient of the particle was calculated on the base of values of the force per unit length;
- the results for similar particles were averaged;
- average results were approximated by analytical equations used in the calculations.

The power of the interaction between the stream and the streamlined object was described by the following formula (Bertin 2002):

$$F = C_x \cdot \rho S \cdot \frac{V^2}{2} = C_x \cdot \rho\, \omega L \cdot \frac{V^2}{2}, \qquad (10)$$

S – cross-sectional area in a streamlined object, m^2;
V - velocity of the stream relative to the object, m/s.

To generalize the characteristics and make them less dependant on the size of the particles (*B* and *L*) and stream conditions, the force per unit length, ie, force, referred to the length of the object, was used. So the coefficient C_x is:

$$Cx = \frac{\left(\frac{F}{L}\right)}{\rho B \cdot \frac{V^2}{2}} = \frac{2\left(\frac{F}{L}\right)}{\rho B \cdot V^2}, \qquad (11)$$

Particles with the width of 4, 15 and 25mm and the thickness of 0.2, 0.5 and 1mm during the simulation were located with the wide side along and across the stream. An example of the dependence of the force per unit length on the rotation speed of the particles is shown in Fig. 5.

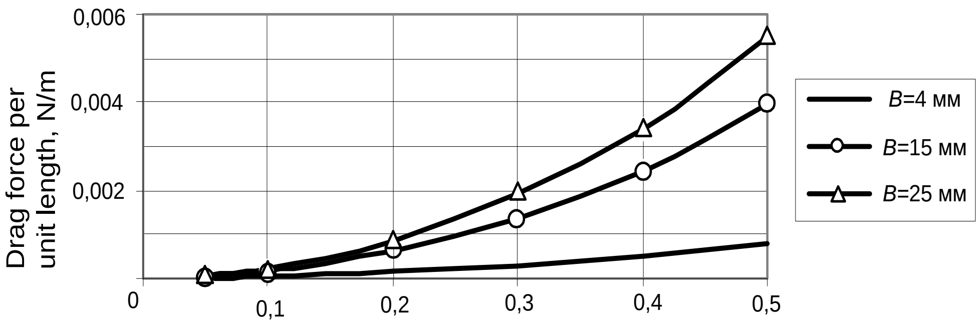

Fig. 5.
The force per unit length influencing the particle with the width B perpendicular to the stream.

As the result of the calculations according to equation (11), averaging the results and the approximation of the curves with the help of MatLab program, new equations were created to determine the coefficient *Cx* for each group of particles with the accuracy of about 10%.

For particles with the width *B*, located along and across the width of stream, the equationsare:

$$Cx = -3.449 + \frac{407.14}{\sqrt{Re}}, \quad Cx = 1.3293 + \frac{2.5227}{\sqrt{Re}}, \qquad (12)$$

Equations (12) were obtained for the argument equaled to the *Re*. Although it is a generally accepted criterion for the environmental streams, it is inconvenient for practical calculations of the movement of wood particles in the systems of orientation because secretly contains the sizes of the particles and their speed, which must be analytically integrated into the calculation. In our particular case, it is more convenient for analysis to express *Cx* as a function of particle velocity relative to the air.

For particles located with the width *B* along and across the stream the equations are the following:

$$C_x = -3.449 + \frac{11.218}{\sqrt{V}}, \quad C_x = 1.238 + \frac{0.15}{\sqrt{V}}, \qquad (13)$$

After substituting (9) into (8) they become:

$$M = K\int_0^R A r^3 \cdot dr + \int_0^R \frac{C}{\sqrt{\omega}\sqrt{r}} \cdot r^3 dr = K \cdot A\int_0^R r^3 dr + \frac{K \cdot C}{\sqrt{\omega}}\int_0^R \frac{r^3}{\sqrt{r}} dr, \qquad (14)$$

Equation (18) contains two integrals:

$$\int_0^R r^3 dr = \frac{R}{4} \text{ and } \int_0^R \frac{r^3}{\sqrt{r}} dr = \frac{2}{7} R^3 \sqrt{R}, \qquad (15)$$

After substituting (15) into (14) the equation is:

$$M = \frac{K \cdot A \cdot R^4}{4} + \frac{2K \cdot C \cdot R^3 \cdot \sqrt{R}}{7\sqrt{\omega}}$$

Taking into account (8), the braking torque is:

$$M = \frac{\rho\, m A \cdot R^4}{4} \cdot \omega^2 + \frac{2\rho\, m C \cdot R^3 \cdot \sqrt{R}}{7} \cdot \frac{\omega^2}{\sqrt{\omega}}, \qquad (16)$$

Then two notations were introduced:

$$a = \frac{\rho\, m A \cdot R^4}{4}, \quad b = \frac{2\rho\, m C \cdot R^3 \cdot \sqrt{R}}{7}, \qquad (17)$$

Finally, the dependence of aerodynamic braking torque on the size of the particle and its angular velocity can be expressed as:

$$M = a \cdot \omega^2 + b \cdot \frac{\omega^2}{\sqrt{\omega}}, \qquad (18)$$

In order to determine the law of motion of a particle, Newton's second law for rotating particles must be used:

$$J\frac{d\omega}{dt} = -M, \qquad (19)$$

J - is the inertia moment of the particle relative to the axis OO^I, kg•m^2.

For a plate with mass *m* and length *L*, the inertia moment is (Landau 1976):

$$J = \frac{1}{12} m \cdot L^2 = \frac{1}{12} m(2R)^2 = \frac{m \cdot R^2}{3}, \qquad (20)$$

After substituting (23) into (22) the equation is:

$$\frac{d\omega}{dt} = -\frac{3}{m \cdot R^2} \cdot \left(a \cdot \omega^2 + b \cdot \frac{\omega^2}{\omega}\right), \qquad (21)$$

Then both sides of this differential equation (21) are integrated:

$$\omega = -\frac{3}{m \cdot R^2}\int\left(a \cdot \omega^2 + b \cdot \frac{\omega^2}{\sqrt{\omega}}\right) dt, \qquad (22)$$

Particle mass *m* is not included into the coefficients (17), so, by (22), it determines the speed of rotation of the particle in the inverse proportion.

Equation (22) is nonlinear, so numerical methods of integration are suitable. In this case the simulation modeling with the help of Simulink software package MatLab was used.

The general scheme of a model for flat particles is shown in Fig. 6.

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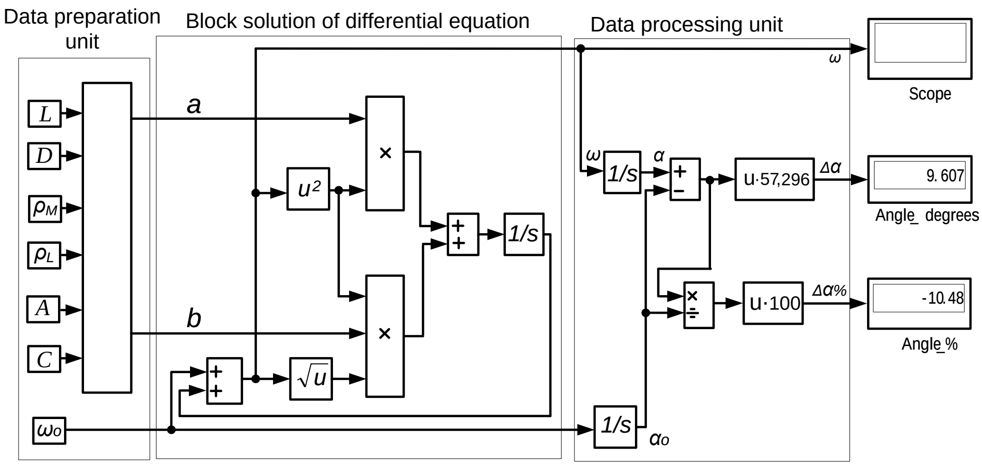

Fig. 6.
Simulation model of a flat particle rotation.

Data preparation unit calculates the coefficients of equation (22), solution unit solves differential equations (22) integrating its right side. The processing unit calculates the angular velocity of the particle moving temporally. In this case, two values of the angular deviation of the particle are calculated: the first one includes the air drag and the second (ideal) one does not include these forces. These values are displayed on the monitors Angle-degrees (in degrees) and Angle % (as a percentage of the ideal value). Oscilloscope Scope demonstrate the process of changing of the angular velocity of a particle moving temporally. Modeling was performed for air density 1,204kg/m^3, its kinematic viscosity 1,51•10^{-5}m^2/s and particle density 400kg/m^3.

The width of the particle *B* moving against the stream has no effect on the slowing of the particle rotation. This conclusion results from equations (17) and (18). The coefficients *a* and *b* in (17) are directly proportional to the width of particle *B*. However, the mass of the flat particle determined by formula (3), in the formula of inertia moment (20) is also proportional to the width of particle *B*.

If *R* = *L* / 2, then, after reductions, the result is:

$$\omega = -\frac{12}{h\cdot\rho_M}\cdot\int_0^R\left(\frac{\rho_L\,\nu L^3}{16}\cdot\omega^2+\frac{\rho_L\,\sqrt{\nu}L^2\cdot\sqrt{L}}{7\sqrt{2}}\cdot\frac{\omega^2}{\sqrt{\omega}}\right)dt\,, \qquad (23)$$

On the other hand, the thickness of particle *H* has an effect on deceleration rate. The larger the thickness is, the less a particle rotation slowing is. This can be explained by the increase of *H* that leads to the increase of the inertia moment of the particle, having little effect on the drag. However, air drag also increases due to the increased effective surface area of the particle in the air with the increasing of its thickness *H*. This consequently leads to an increase in deceleration rate of the particle.

The resulting numerical simulation of the velocity field in the stream around the particles (excluding its falling) is shown in Fig. 7, and the graphs of the angular velocity of the particle - in Fig. 8.

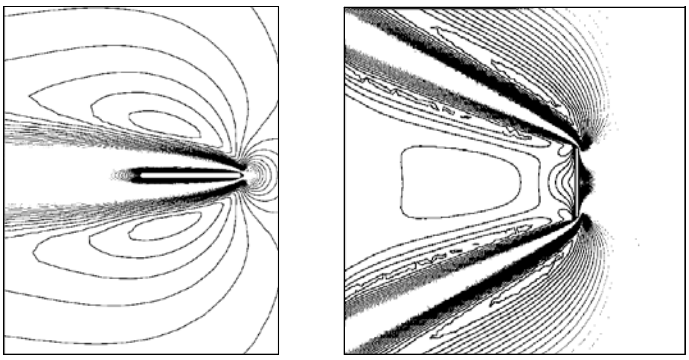

Fig. 7.
Velocity field in the particle motion with the width 20mm, the thickness 1mm:
a - flat side along the stream; b - flat side perpendicular to the stream.

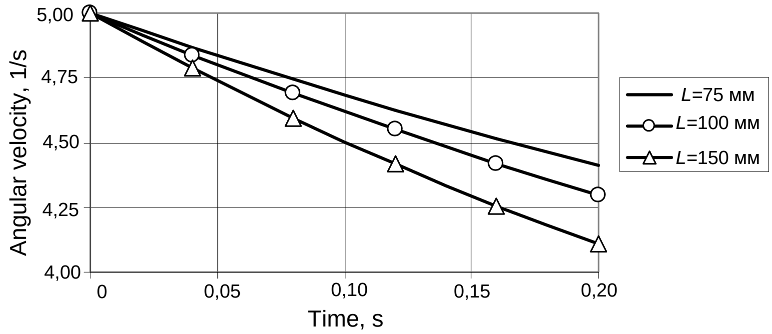

Fig. 8.
Dependence ω = f(t) for a particle with the following parameters: H = 0,5mm, B = 20mm, moving against the stream by its narrow side.

CONCLUSION

The modeling of translational motion of flat particles enabled to calculate the value of particle fall time depending on its size and the height of the fall. This time depends on the thickness and density of the particles and does not depend on its length and width. Due to the random combinations of process parameters, a deviation from the average time of the fall was also observed.

During rotation of the particle the force per unit length of the drag influencing it increases linearly with the size of the particle. The angular velocity of the particles relative to the initial rate reduced by the law close to the line and the orientation time for the angular velocity of the particles sized 150mm and 75mm is reduced by 20% and 12%, respectively. This reduction increases linearly with the decreasing particle density. Thus, for the full range of particle diameters aerodynamic drag coefficient k in (5) ranges from 1.12 to 1.20, depending on the particle size, density, initial rotational speed and time reversal, which is proportional to the height of the fall in orienting device.

The accuracy of the calculations was increased by the fact that the drag coefficient in both models was determined in the numerical experiment.

The results of the study could help to reduce the angle of spread of the particles in the formed mat of wood strand and, thus, to increase the bending strength of produced boards OSB.

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