IMPROVING THE EFFICIENCY OF WOOD CHIPPING OPERATIONS
/
ПОВЫШЕНИЕ ЭФФЕКТИВНОСТИ ПРОЦЕССОВ ПРОИЗДВОДСТВА ДРЕВЕСНОЙ ЩЕПЫ

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ABSTRACT
The paper presents a novel approach to the problem of utilizing wood chips as a valuable raw material. It shows how advances in machine vision can enable the conversion of wood chips from waste to a valuable resource. Empirical dependencies that are used to calculate the slip velocity of wood chips on the walls of the tank have been obtained. The problems of particle–fluid and particle–particle interactions within the flow are solved. Findings may be applied not only in countries with traditionally developed wood industries but also in many others.

АННОТАЦИЯ
В работе представлен новый подход к проблеме использования древесной щепы как ценного сырья. Показано, как на базе достигнутых успехов в деле машинного зрения можно из древесной щепы – отхода сделать древесную щепу – ценное сырьё. Получены эмпирические зависимости, которые были использованы для расчета скорости скольжения древесной щепы на стенках резервуара. Решена задача коллективного взаимодействия потока щепы между собой и с несущим флюидом. Результаты работы могут быть использованы не только в странах с традиционно развитой древесной промышленностью, но и во многих других.

INTRODUCTION
In recent years, approaches to the problem of sorting wood chips have been increasingly gravitating towards solutions based on machine vision *(Verheyen et al., 2016, Kuchin et al., 2020)*. Sorting becomes especially important if production involves substandard wood waste, as this process has a strong and positive environmental effect. Secondary wood that has no defects can serve a good source of wood chips for the chipboard production *(Merrild and Christensen, 2009)*. Finding application for this type of material reduces CO2 emissions during the creation of construction supplies. Secondary wood is usually very dry as compared to primary wood, and the chipboard industry uses 15% less energy when using secondary wood chips.

Designing mathematical models for the movement of wood chips will help find the optimal conditions for better productivity. For comparison, other authors *(Rößler et al., 2018*) presented a simulation of moving wood chips and resin droplets within a resin blending mixer. In particleboard production, the mixing of wood chips and resin droplets is a sub-process called gluing or resin metering (*Papadopoulos, 2006*). *Rudak et al. (2018)* modelled the movement of wood chips with the aim of ensuring production safety. *Polyanin et al. (2019)* partially solved our problem while laying emphasis on the problem of wood chips sorting. *Prosvirnikov*

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et al. (2017) discussed mechanical changes that occur in wood when chipping. The geometry of resultant wood chips has been modelled too *(Fomin, 2017)*.
The wood chip-fluid interaction was considered by *Scherer et al. (2016)*, but the present study takes the behaviour of wood chips inside the unit into account in greater detail, i.e., we investigated the collective effect of chip-chip interaction in a semi-empirical way. The importance of mathematical modelling of timber processing operations is emphasized by *Rahman et al. (2018)*. The mentioned research demonstrated the increment of the product cost and the overall improvement in economic efficiency after mathematical optimization of the production process. *Agu et al. (2019)* contributed undertakings associated with the wood chip-fluid interaction modeling.

Wood chip products are usually transported by pneumatic conveyors *(Kaplan and Celik, 2018)*. However, these systems also have a number of drawbacks, among them is the formation of dead zones, especially in wood chip storage tanks *(Alakoski et al., 2016)*. Eliminating these shortcomings is essential to improve the efficiency of production lines, since the occurrence of dead zones may negatively affect the flow behaviour of wood chips, resulting in a blockage. The accumulation of wood chips in a tank together with wood dust and the overheating of electric air pumps significantly increase the fire risk. Theoretical studies relate mainly to the movement of elements of a regular shape and are based on the mathematical models for granular media that have neither analytical solutions, nor calculation methods, nor closing relations *(Rahman et al. 2018)*. Experimental studies of the gravity-driven movement are qualitative and relate mainly to the model elements, which does not allow for the application of results in the practical context. The aim of this paper is to introduce a new approach to the problem of utilizing wood chips as a valuable raw material. Specifically, the paper presents an algorithm for deciding on an optimal travel mode of wood chips in tanks with axial symmetry, which may be of use when designing tanks with only one discharge hole.

MATERIALS AND METHODS

In terms of potential and viscous movement of chipped wood that is dependent on the structural and physico-mechanical properties of material being pushed, the model based on Navier-Stokes equations is of main interest. The movement of falling material in the gravitational field of the tank is considered a non-Newtonian fluid with a viscosity corresponding to the apparent viscosity of the granular medium. The system of equations for the symmetric movement relative to the vertical axis of the tank, with the stream function ψ and the vortex function ω, in the coordinate system (*z;r)* is as follows (*Bedrossian*, *2016*):

$$\rho + r^2\left[\frac{\partial}{\partial z}\left(\frac{\omega}{r}\frac{\partial\psi}{\partial r}\right) - \frac{\partial}{\partial r}\left(\frac{\omega}{r}\frac{\partial\psi}{\partial z}\right)\right] = \frac{\partial}{\partial z}\left[r^3\frac{\partial}{\partial z}\left(\frac{\mu+\omega}{r}\right)\right] + \frac{\partial}{\partial r}\left[r^3\frac{\partial}{\partial r}\left(\frac{\mu+\omega}{r}\right)\right] \tag{1}$$

$$\omega = -\frac{1}{r}\left(\frac{\partial^2\psi}{\partial r^2} + \frac{\partial^2\psi}{\partial z^2} - \frac{1}{r}\frac{\partial\psi}{\partial r}\right) \tag{2}$$

where:

ρ is the apparent density of the granular medium, [kg/m^3];

μ is the apparent viscosity of the granular medium, [Pa·s].

Equations (1) and (2) are related and non-linear. They were solved numerically using the finite-difference methods (FDM). In contrast to a viscous fluid with a velocity between the fluid and the solid wall assumed to be zero, a granular medium does not meet this condition. Depending on the value of the wall surface roughness, which is taken into account by the external friction coefficient *f,* the slip velocity of particles in the vertical and inclined channel of the conical tank can vary from zero to the final value. On the solid boundary (vertical and inclined walls), the value of the vortex function was set as follows.

For the impermeable wall, the stream function was ψ = const, which corresponded to the total pass on the region under consideration. The vortex function ω for the inclined wall corresponded to the conical bottom of the vertical cylindrical tank. To solve the mathematical model, a program was developed for calculating the movement of chipped wood with axial symmetry in a tank with a central discharge hole. The boundary condition for the corresponding vortex function was set as follows:

$$\omega_N = \frac{2}{r\,tg\,(\delta\_)}\left(\frac{\partial^2\psi}{\partial r\partial z}\right) - 2\left(\frac{1}{r}\frac{\partial^2\psi}{\partial r^2} - \frac{1}{r^2}\frac{\partial\psi}{\partial r}\right) \tag{3}$$

where:

δ is external friction angle.

Experimental studies to find the coefficients of external and internal friction were carried out using a shearing apparatus consisting of a shear box, dynamometer and a drive (Fig.1).

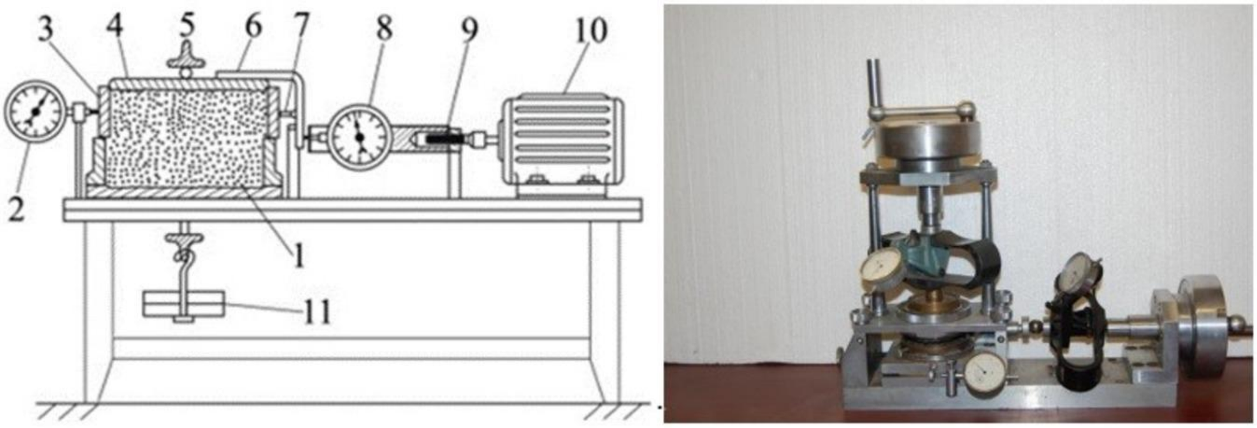

Fig. 1 - A shearing apparatus (schematic view)

1- fixed bottom platen; 2- a dial indicator ;3- a movable side platen, 4 -movable upper platen, 5 - a bent arm; 6,7,8 - a 0.05 N dynamometer,9- a drive, 10 - shear box; 11- weights.

The shearing apparatus allows for measuring the coefficient of internal friction and the shear resistance of the fluid. To find the coefficient of external friction, the stationary half of the shear box was replaced with a wall material model.

The movement of wood chips was experimentally studied on two units, industrial and pilot. The industrial unit was a cylindrical tank feeding wood chips into the pneumatic conveying system. The pilot unit was a physical simulator (Figure 2). The design of the simulator showing a cross-sectional view of a cylinder-conical tank made it possible to capture photos and video of the wood chips and model objects (i.e. coloured balls of varying sizes) moving through the tank.

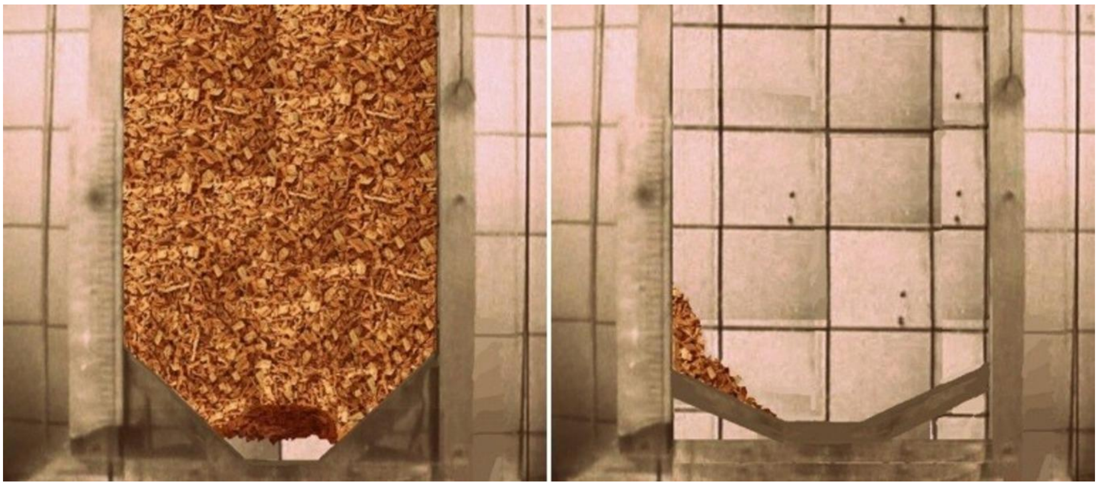

Fig. 2 - A cylinder-conical tank simulator

The bulking factor F_b was investigated on a physical simulator using the method of polynomial least squares. The results are presented in Figure 3. The dependence of the bulking factor on the coordinate was expressed as follows:

$$F_{b/axos} = 0.19 \cdot \bar{z}^3 - 0.44 \cdot \bar{z}^2 + 0.265 \cdot \bar{z} + 0.31 \quad (4)$$

$$F_{b/wall} = 0.0023 \cdot \bar{z}^3 + 0.061 \cdot \bar{z}^2 - 0.132 \cdot z + 0.39 \quad (5)$$

To identify the effect of specific factors on the physico-mechanical characteristics of the fluid passing through the tank, the following parameters of wood chips were measured: particle size, water content, and temperature. As it turned out, the bulking factor and the friction coefficients were bound in a positive correlation. The higher the bulking factor, the higher the friction coefficients.

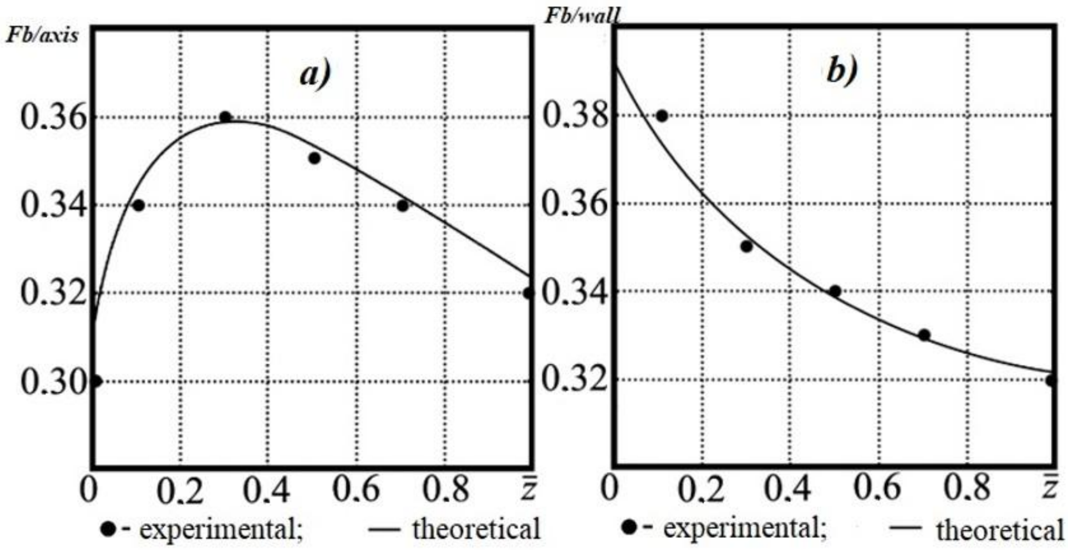

Fig. 3 - The bulking factor distribution (a) along the axis of the tank; b) along the tank wall

The shear resistance K value also increases with the bulking factor F_b and the compaction load P. The coefficients of internal and external friction, however, were not dependent on the compaction load. The theoretical angles of internal δ_+ and external δ_- friction were determined by the following formula:

$$\delta_{+(-)} = Arc\,\sin\left(F_b\left|\frac{a}{\frac{\partial F_b}{\partial z}} - \frac{b}{\frac{\partial F_b}{\partial r}+B}\right|\right) \tag{6}$$

where: *a* = 5.2897; *A* = 3.2058; *b* = 0.00019; *B* = – 0.00033 are constants.

RESULTS

Experimental measurement of the coefficients of internal and external friction (Figure 4) were carried out using a shearing apparatus.

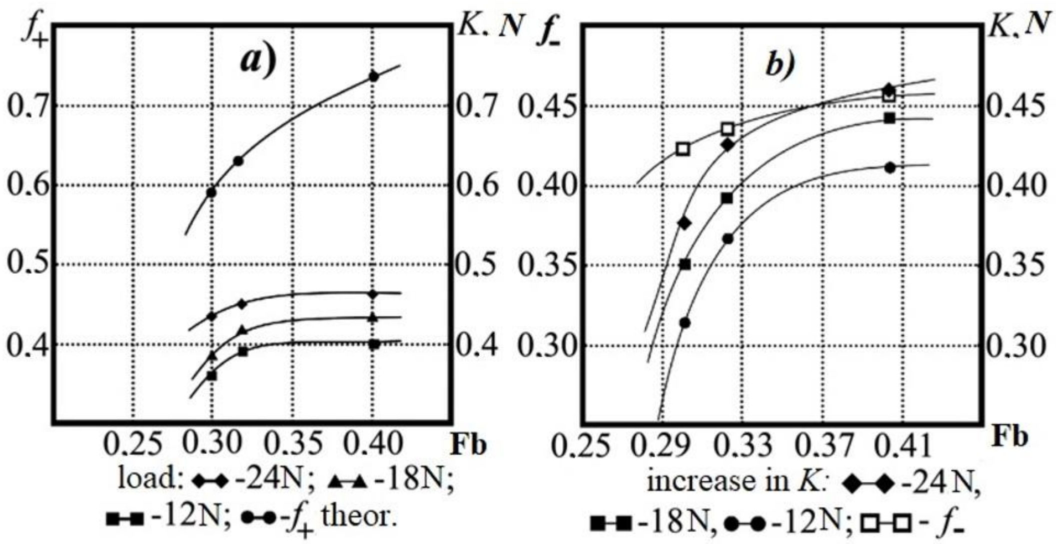

Fig. 4 - Dependence between friction coefficients and bulking factor
(a) internal friction coefficient; b) external friction coefficient)

The physico-mechanical properties of chipped wood demonstrated dependence not only on its structure but also on the fractional size distribution of wood chips, their water content, and temperature (Fig.5).

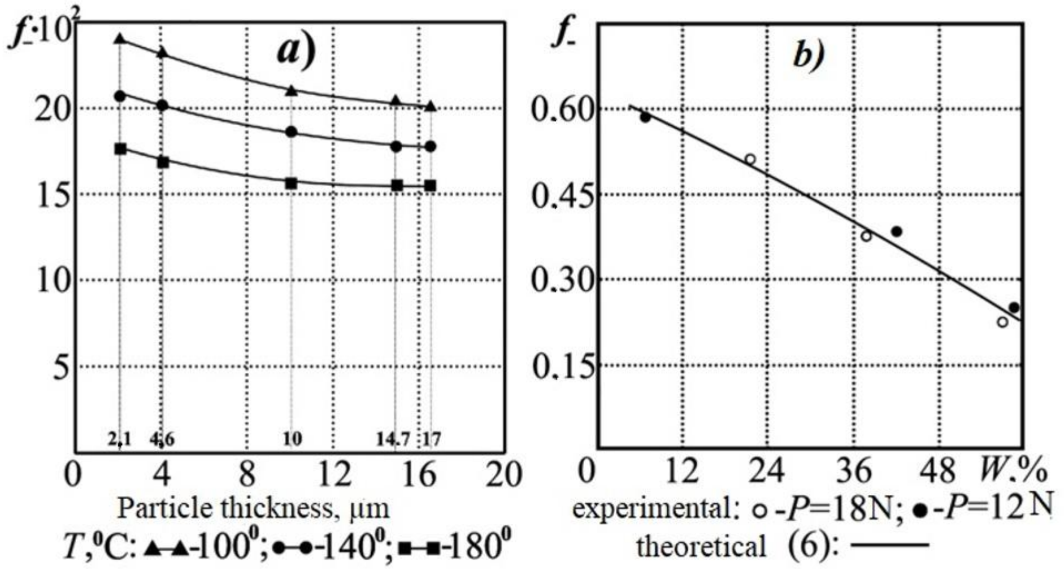

Fig. 5 - The dependence of external friction coefficient on the following parameters of wood chips: temperature (a) and water content (b)

In addition to the experimental dependence of the external friction coefficient f_-, Figure 5b shows a polynomial dependence (7):

$$f_W = 0.634 - 0.622 \cdot W - 0.092 \ \cdot W^2 \tag{7}$$

Experimentally, the study revealed dependence between the movement of wood chips and the following parameters:

– *transportation parameters:* discharge intensity; the number of discharge holes; and the way in which wood chips are fed into the tank;

– *tank geometry:* the angle of inclination of walls in the conical bottom; transition radius defining the transition of the cylindrical wall to the conical bottom; transition radius defining the transition of the conical bottom to the cylindrical channel of a discharge hole; the presence/absence of reinforcement on the inner walls of the cylindrical section (grooves, protrusions, etc.);

– the ratio of cylindrical section diameter to the equivalent diameter of a chip, D/d_e;

– the ratio of cylindrical section diameter to the discharge hole diameter, D/D_d,

– the ratio of the discharge hole diameter to the equivalent diameter of a chip, D_d/d_e;

– the relative fill height, H/D;

– *physico-mechanical parameters of wood chips*: particle density; bulking factor; coefficients of internal and external friction.

To eliminate the formation of a dead zone with wood chips accumulating before the hole in a mound arrangement, the D_d / d_e ratio was calculated by the following formula:

$$\frac{D_d}{d_e} = \frac{\sigma \cdot f_+ f_-}{p \cdot g \cdot (1 - F_b) \cdot \delta} \tag{8}$$

The graphical data in Figure 5b showed that the minimum relative diameter of a discharge hole depended on the maximum length of the particle passing through it *l*.

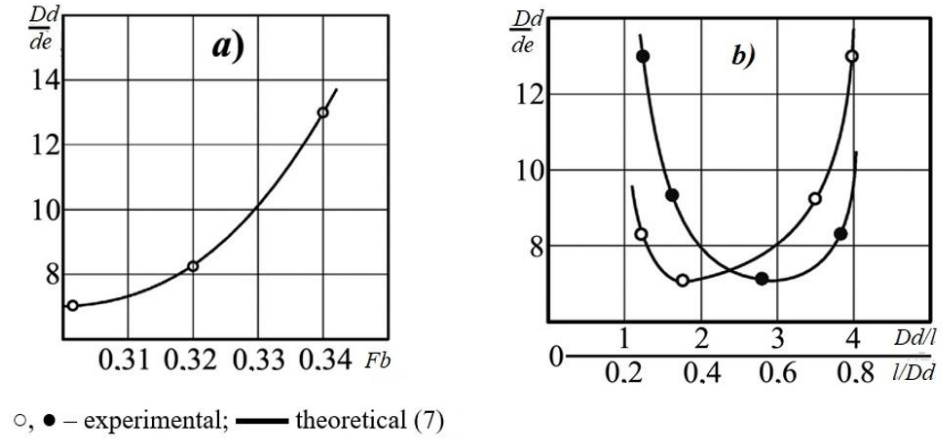

Fig. 6 - The dependence of a relative discharge hole diameter on the bulking factor (a) and the relative particle size (b)

With l/D_{d} of 0.56, the minimum value of the D_d/d_e ratio will be 6.99. There is a negative correlation between these two dependences. With larger particles, the likelihood of a dead zone was higher. With smaller particles, the bulking factor increased and thus caused the growth of the internal friction coefficient f_+. The implication was a dead zone.

Note that the equation (7) does not take into account the effect of the fill height H and the cross-sectional diameter of the cylindrical section of the tank D_c. After substituting these two parameters into the equation (7), the resultant dependence for the active flow channel diameter D_f can be expressed as follows:

$$D_f = D_{d\ min} + k_1 \cdot \left(\frac{H - k_2 \cdot D_c}{1 + k_3 \cdot tg\theta}\right) \cdot tg(\theta) \tag{9}$$

where: $D_{\mathrm{d\ min}}$ is the minimum discharge hole diameter acceptable to ensure a discharge of wood chips without the formation of a dead zone; k_1, k_2, k_3, θ – experimental coefficients.

As it can be seen from formulas (7) and (8), the active flow channel diameter can be increased by adding to the fill height H and to the value of the H/D_c ratio.

The simulation and experimental results of the fluid movement analysis are presented in Figure 6. It turned out that theoretical and experimental trajectories of a wood chip mass almost match. As per the results of theoretical calculation and physical simulation (Figure 7), modifications to the industrial tank were introduced (Figure 8). It was decided to install a fill height control device because changing the discharge hole diameter would require a cost-intensive modification of various metal parts. The final solution is cheap and efficient.

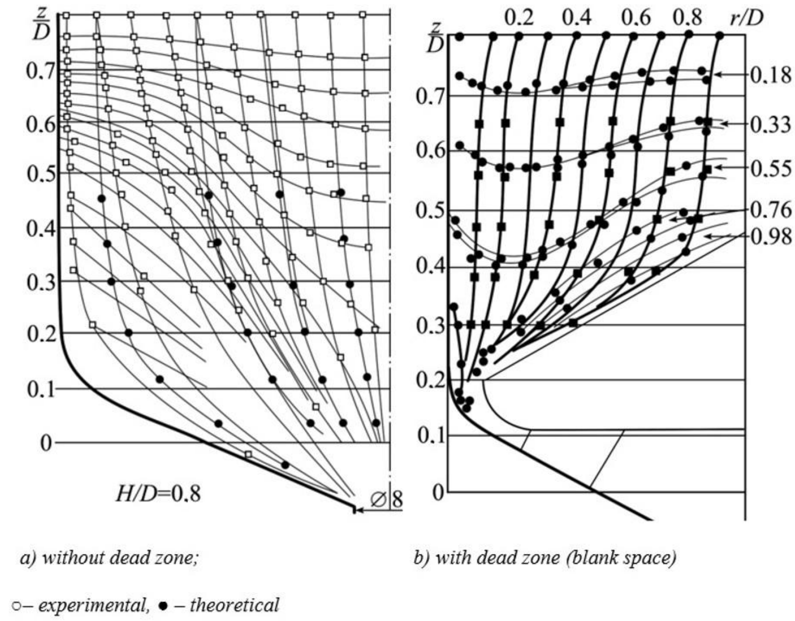

Fig. 7 - A comparative presentation of theoretical and experimental trajectories of chipped wood masses passing through the slope section of the cylinder-conical tank

Fig. 8 - A modified industrial tank assembly

CONCLUSIONS

The study offers a novel approach to the problem of efficient and reliable pneumatic conveyance of wood chips. Empirical dependencies have been obtained that were used to calculate the slip velocity of wood chips on the walls of the tank. Tanks are recommended to have a conical bottom with an angle of inclination between 25° and 30° to avoid the formation of dead zones. Additionally, a ratio of tank diameter to discharge hole diameter is recommended to be ≤ 60, that is, a tank shall have a diameter that does not exceed 60 diameters of the discharge hole. The paper builds a semi-empirical simulation of the wood chips flow that was monitored throughout the entire production process from the sorting phase. The problems of particle-fluid and particle-particle interactions within the flow are solved. Using the proposed approach will improve the reliability of pneumatic conveyance with resultant savings in downtime.

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