MODELING OF MECHANICAL AND TECHNOLOGICAL PROCESSES OF THE AGRICULTURAL INDUSTRY
/
МОДЕЛЮВАННЯ МЕХАНІЧНИХ ТА ТЕХНОЛОГІЧНИХ ПРОЦЕСІВ СІЛЬСЬКОГОСПОДАРСЬКОЇ ПРОМИСЛОВОСТІ

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SUMMARY

Modern theoretical researches on the mechanical and technological processes for agricultural industry can be summarized by analytical methods, which lead to the compilation of complex systems of differential equations with boundary and initial conditions. These systems practically cannot be solved by traditional methods, so there is a necessity in their numerical solution via computer modeling. The molecular dynamics method and discrete element method, both of them based on the conception of a discrete structure of a substance, are the most interesting ones among all existing modern computer modeling methods for the mechanical and technological processes of agricultural industry. The purpose of these researches is to carry out the numerical modeling for some mechanical and technological processes for agricultural industry using the Star CCM+ computer software. There have been provided the results of the numerical modeling in the Star CCM+ computer software of the following mechanical and technological processes: mixing of components in a stream-type mixer-feeder, distribution of the straw underlay by the rotor spreader for the non-leash cow maintenance, formation of the pseudo-liquefied seed layer in the hydro-pneumatic seeding machine's intake chamber, transferring of the oil crops seeding material with the air stream power, functioning of the photoelectric seed separators executing mechanism, technological process of the seed separation on an inclined vibrating surface. The given results point about the wide area of implementation of the numerical modeling for theoretical researches of mechanical and technological processes for agronomical manufacturing industry.

РЕЗЮМЕ

Сучасні теоретичні дослідження механічних і технологічних процесів сільськогосподарської обробної промисловості можна підвести до аналітичних методів, що призводить до складання складних систем диференціальних рівнянь з граничними та початковими умовами. Ці системи практично не можуть бути вирішені традиційними методами, тому в їх чисельному вирішенні необхідне використання комп'ютерного моделювання. Метод молекулярної динаміки та метод дискретних елементів, обидва з яких базуються на концепції дискретної структури речовини, є найбільш цікавими серед усіх існуючих сучасних методів комп'ютерного моделювання механічних та технологічних процесів сільськогосподарської обробної промисловості. Метою цих досліджень є проведення чисельного моделювання деяких механічних та технологічних процесів для сільськогосподарської промисловості за допомогою програмного забезпечення Star CCM+. Наведені результати чисельного моделювання в комп'ютерній програмі Star CCM+ наступних механічних та технологічних процесів для аграрної промисловості: змішування компонентів у змішувачі-фідері потокового типу, розподіл соломистої підстілки роторним розкидачем для технологічного обслуговування безприв'язних корів, формування шару псевдозрідженого насіння в *гідравлічно-пневматичній впускній камері посівної машини, транспортування посівного матеріалу олійних культур повітряним потоком, функціонування механізму фотоелектричних насіннєвих сепараторів, технологічний процес сепарації насіння на нахиленій вібраційній поверхні. Дані результати свідчать про широку область застосування цифрового моделювання для теоретичних досліджень механічних та технологічних процесів сільськогосподарської промисловості.*

INTRODUCTION

Modern theoretical researches on the mechanical and technological processes for agricultural industry can be summarized by analytical methods, which lead to the compilation of complex systems of differential equations with boundary and initial conditions *(Johnson K.L., 1987)*. These systems practically cannot be solved by traditional methods, so there is a necessity in their numerical solution via computer modeling.

The molecular dynamics method and discrete element method, both of them based on the conception of a discrete structure of a substance, are the most interesting ones among all existing modern computer modeling methods for the mechanical and technological processes for agricultural manufacturing industry. The molecular dynamics method consists of representing the substance as an aggregation of interacting particles – material points or solid bodies. Their movement is described by the classic mechanics equations. During the particles movement modeling, the molecular dynamics method solves the Cauchy problem on every step with iterative methods – performing an integration of the differential equations with determined initial conditions. The best known software for calculations using the molecular dynamics method is: AMBER, CHARMM, GROMACS, GROMOS and NAMD. The discrete element method can be considered as a generalization of the finite element method. During the modeling with this method the initial locations and velocities of particles must be pre-determined. After this, basing on these initial data of the particles interaction physical laws, the active forces for each particle must be determined. Following this, it's possible to consider various interaction laws; it's sufficient to have a solvable equation for their description. For each particle, the method requires to calculate the resultant force and also to solve the Cauchy problem on the selected time interval. The result for these calculations will be the initial data for the next step. The best known software for the discrete elements method realization is: Chute Maven (Hustrulid Technologies Inc.), PFC2D i PFC3D, EDEM (DEM Solutions Ltd.), GROMOS 96, ELFEN, MIMES, PASSAGE and Star CCM+. The purpose of this research is to perform the numerical modeling for some mechanical and technological processes for agricultural manufacturing industry in the Star CCM+ computer software.

MATERIALS AND METHODS

During the finite elements method modeling process in the Star CCM+ software the initial locations and velocities of the particles and substance stream must be pre-determined. Then, basing on these initial data for the contact interaction physical laws, the forces that act on each particle in each time interval, are being calculated. For each particle, the resultant force is being calculated and the Cauchy problem is solved for a given time interval. The results of this iteration are the initial data for the next step. The following models were selected as physical models for the numerical modeling: k-ε-model of the separated stream turbulence, field of the gravity force, Van-der-Waals real gas model or the non-pressed fluid model, the discrete elements model, the multiphase interaction model. The discrete elements method is based on the momentum conservation law for the Lagrange multiphase stream models.

To perform the research on the particles' movement process under the substance stream affect, it is required to determine the mathematical apparatus that allows obtaining the trajectories, force diagrams and slip values during the particles movement in the substance stream with the velocity gradient.

Let's begin by composing the differential equation for the movement of one particle in the dedicated substance stream area *(Gumerov N., Duraiswami R., 1998)*:

$$\begin{cases} \Omega_p \cdot \rho_p \dfrac{d_p \overline{V_p}}{dt} = \overline{F} \\ \dfrac{d_p \overline{S_p}}{dt} = \overline{V_p} \\ \dfrac{d_p}{dt} = \dfrac{\partial}{\partial t} + \overline{V_p} \cdot \overline{\nabla} \end{cases} \tag{1}$$

Where Ω_p – particle value, m^3;

ρ_p – particle density, kg/m^3;

$\overline{V_p}$ – particle movement velocity vector, m/s;

$\overline{S_p}$ – particle displacement vector, m;

$\overline{F}$ – vector of the resulting force applied to particles, N.

The effective diameter of the particle is one of its characteristics, which is defined as a diameter of an equal-sized sphere. So, the equivalent particle value can be defined by the equation:

$$\Omega_p = \frac{\pi \cdot D_p^3}{6} \tag{2}$$

Where D_p – particle effective diameter, m.

Attempts to solve this equation system (1) are combined with certain difficulties that can be reduced to the following:

a) the total number of forces, that affect the particle in the substance stream, are undefined, because the processes of the particle behaviour within the stream are not fully described;

b) strict analytical expressions for some expressions in the right part of the equation are unknown (for example, an expression for the hydrodynamic air force).

Forces, that affect the particle during its movement in the turbulent stream, can be divided to the following groups, based on the reasons of their emerging:

1. Forces that are caused by the external force fields affect (weight force) *(Dinesh J., 2009)*:

$$\overline{F_g} = \Omega_p \rho_p \overline{g} \tag{3}$$

where $\overline{F_g}$ – gravity force vector, N.

2. Forces, that are caused by the uneven balance of the pressure on the particle surface during its movement in the substance stream.

2.1 Archimedes force *(Dinesh J., 2009)*:

$$\overline{F_A} = \Omega_p \rho_a \overline{g} \tag{4}$$

Where $\overline{F_A}$ – Archimedes force vector, N.

ρ_a – substance density, kg/m^3.

2.2. Force that is caused by the change of the pressure in the direction of the carrying stream movement due to the acceleration *(Gumerov N., Duraiswami R., 1998)*:

$$\begin{gathered} \overline{F_{ac}} = \Omega_p \rho_a \frac{d_a \overline{V_a}}{dt} \\ \frac{d_a}{dt} = \frac{\partial}{\partial t} + \overline{V_a} \cdot \overline{\nabla} \end{gathered} \tag{5}$$

Where $\overline{F_{ac}}$ – force, that is caused by the change of the pressure in the direction of the carrying stream movement, *N*;

$\overline{V_a}$ – substance movement velocity vector, m/s.

2.3. Hydrodynamic Magnus force emerges as a result of an uneven upcoming stream bypassing of the particle. The difference between the stream velocities in different particle perimeter points, which is bypassing, causes the static pressure differential. The reason of the uneven upcoming stream bypassing of the particle can be either its rotating inside the stream, or its persistence in that zones where the stream has a transverse gradient. The value of the Magnus force is proportional to the relative forward velocity and its absolute angular velocity, i.e. *(Kanehl P., 2010)*:

$$\overline{F_{Mag}} = \frac{1}{2}\pi D_p^2 \rho_a V_a^2 C_M \frac{\overline{\omega} \times \overline{V_a}}{\left|\overline{\omega} \times \overline{V_a}\right|}, \tag{6}$$

Where $\overline{F_{Mag}}$ Magnus force, N; C_M – Magnus empirical coefficient; $\overline{\omega}$ – angular rotational velocity vector, s^{-1}.

3. The viscous resistance force, which is caused during the particle movement with some relative velocity in the substance stream *(Hamzaev H.M., 2007)*:

$$\overline{F_D} = \frac{1}{2}\pi D_p^2 \rho_a f_M(Re)\left(\overline{V_a} - \overline{V_p}\right)\left|\overline{V_a} - \overline{V_p}\right|, \tag{7}$$

Where $\overline{F_D}$ – viscous resistance force, N; $f_M(Re)$ – viscous resistance coefficient;

Re_a – Reynolds number.

$$Re_a = \frac{V_a \cdot D_G \cdot \rho_a}{\mu_a}, \tag{8}$$

D_G – hydraulic diameter, m;

To this group we can also add the Basset force, which combines the viscous and inertial impact of the stream to the particle non-stationary movement conditions.

4. Inertial forces, which are caused by the non-stationary particle movement in the substance are:

4.1 Force, which is equivalent to the added mass impact, is presented as:

$$\overline{F_m} = \frac{1}{2}\Omega_p \rho_a \frac{d}{dt}\left(\overline{V_a} - \overline{V_p}\right), \tag{9}$$

and expresses the uprising particle inertia during its non-stationary movement *(Hamzaev H.M., 2007)*. A moderate increasing of the particle mass is caused by the substance elements inertia, so that particle must transfer an additional acceleration. This additional substance movement is equivalent to the movement of some fictitious mass (additional mass), which moves with the same relevant velocity as the particle.

4.2. Basset force *(Zhang S. and other, 2009)*:

$$\overline{F_B} = \frac{6\pi\pi\mu_p^2}{\sqrt{\pi\nu}} \int_\tau \frac{d}{d\tau}\left(\overline{V_a} - \overline{V_p}\right)\frac{d\tau}{\sqrt{t-\tau}}, \tag{10}$$

Where $\overline{F_B}$ – Basset force, N;

ν – kinematic viscosity, m^2/s;

τ – time, s.

Basset force considers an additional particle movement resistance from the stream, which is caused by the particle relevant velocity configuration. Basset force manifests as a momentum particle movement resistance increasing due to the increasing of its inertia.

5. Forces that are caused by the particle mass changing (Meshchersky force) *(Voronenko B.A., Pelenko V.V., Polyakov S.V., 2013)*:

$$\overline{F_M} = \overline{V_p}\frac{dm_p}{dt} \tag{11}$$

Where $\overline{F_M}$ – Meshchersky force, *N; m_p* – particle mass, kg.

6. Summarized force of the contact interaction between particle and the chamber, which is based on the Hertz-Mindlin spring-dashpot contact model *(Komiwes V., Mege P., Meimon Y., Herrmann H., 2006)*:

$$\overline{F_{Dif}} = \beta_p \overline{V_p} \quad (12)$$

Where $F_{contact}$ – force of the interaction between particles and the edge, N;

$$\overline{F_{contact}} = \overline{F_n} + \overline{F_t} \quad (14)$$

$\overline{F_n}$ – normal force component, N;

$\overline{F_t}$ – tangential force component, N.

Normal force component is defined by the following equation:

$$\overline{F_n} = -K_n \overline{d_n} - N_n \overline{V_n}$$

Where K_n – normal coefficient of the spring component rigidity, N/m;

$$K_n = \frac{4}{3} E_{eq} \sqrt{d_n R_{eq}} \quad (16)$$

N_n – normal coefficient of the dashpot component degradation, N/m;

$$N_n = \sqrt{(5K_n M_{eq})} N_{n\ damp} \quad (17)$$

According to the researches (*Johnson K.L., 1987)* tangential component is defined as:

$$\overline{F_t} = -K_t \overline{d_t} - N_t \overline{V_t} \quad (18)$$

if $\left|K_t \overline{d_t}\right| < \left|K_n \overline{d_n}\right| C_{fs}$, and C_{fs} – statistic friction coefficient between particles or a chamber wall. In the other case, the tangential component is defined by the following equation:

$$\overline{F_t} = \frac{\left|K_n \overline{d_n}\right| C_{fs} \overline{d_t}}{\left|\overline{d_t}\right|} \quad (19)$$

where K_t – tangential coefficient of the spring component rigidity, N/m;

$$K_t = 8G_{eq} \sqrt{d_t R_{eq}} \quad (20)$$

N_t – tangential coefficient of the dashpot component degradation, N/m;

$$N_t = \sqrt{(5K_t M_{eq})} N_{t\ damp} \quad (21)$$

N_{damp} – degradation coefficient

$$N_{damp} = \frac{-ln(C_{n\ rest})}{\sqrt{\pi^2 + ln(C_{n\ rest})^2}} \quad (22)$$

R_{eq} – equivalent radius of particles A and B, m;

$$R_{eq} = \frac{1}{\frac{2}{D_A} + \frac{2}{D_B}} \quad (23)$$

M_{eq} – equivalent mass of particles A and B, kg;

$$M_{eq} = \frac{1}{\frac{1}{M_A} + \frac{1}{M_B}} \quad (24)$$

E_{eq} – equivalent Young module of particles A and B, Pa;

$$E_{eq} = \frac{1}{\frac{1-\nu_A^2}{E_A} + \frac{1-\nu_B^2}{E_B}} \quad (25)$$

G_{eq} – equivalent module of the particles A and B displacement, Pa;

$$G_{eq} = \frac{1}{\frac{2(2-v_A)(1+v_A)}{E_A} + \frac{2(2-v_B)(1+v_B)}{E_B}} \quad (26)$$

M_A, M_B – particles A and B mass, kg;

d_n, d_t, – duplication coefficient for the normal and tangential direction in contact points;

D_A, D_B – particles A and B effective diameters, m;

E_A, E_B – particles A and B Yung module, Pa;

v_A, v_B - particles A and B Poisson coefficients;

$\overline{V_n}$, $\overline{V_t}$ – normal and tangential components of the particle surface relevant velocity in the contact point, m/s.

For the interaction process between a particle and a wall the (13)-(26) are adequate, but, for the wall, the radius is defined as $D_{wall} = \infty$ and the mass as $M_{wall} = \infty$. As a result, expressions (23)-(24) turn into:

$$R_{eq} = D_p/2 \qquad M_{eq} = M_p \quad (27)$$

RESULTS

In order to demonstrate the results of the numerical modeling in the Star CCM+ software, let's consider some mechanical and technological processes for agricultural manufacturing industry.

1. The process of the stream-type mixer-feeder operation has been theoretically researched and the mathematical models of the constructive, technological and regime parameters impact on the quality indexes of its operation have been developed *(Shevchenko I.A., Aliyev E.B., Doruda S.O., 2013)*. The physical mathematical models of the streaming feed mixing process, which is used as a base for the mobile mixer-feeder, has been built within the Star CCM+ software (fig. 1). This physical mathematical model of the streaming feed mixing allows defining the constructive and technological parameters for the mobile mixer-feeder depending on the ration and physical mechanical properties of the feeding mix components with optimal quality, quantity and energy indexes of the mixing process.

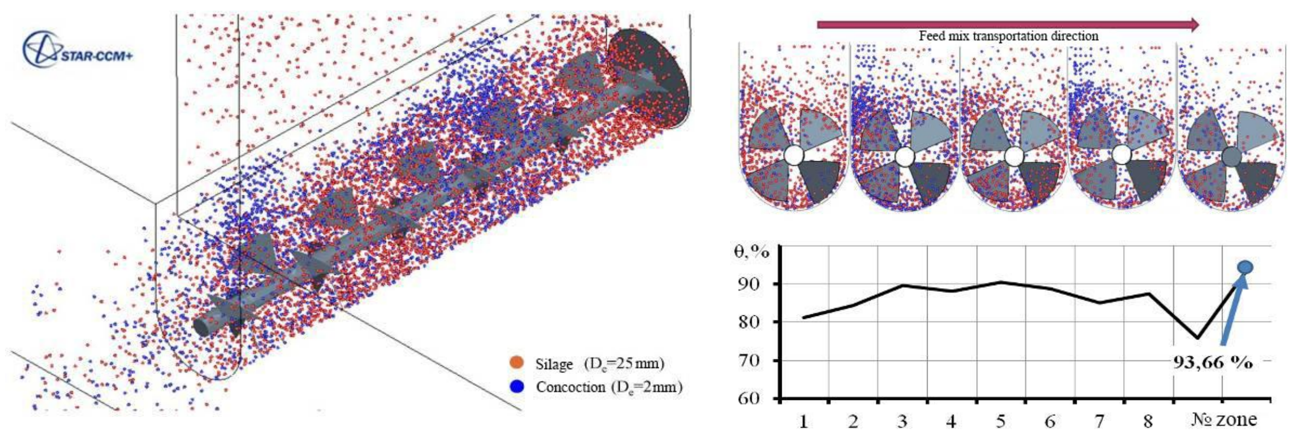

Fig. 1 – Visualization of the mobile mixer-feeder streaming feed mixing process and the dynamic of its homogeneity changing

2. The constructive and technological schemes of the working parts of the rotor straw underlay spreader for the non-leash cow maintenance has been theoretically substantiated *(Luts S.M., Aliyev E.B., 2014)*. The presence and absence of the sealing or directional plate have been used as research objects. The straw particles flight distance and the coefficient of the variation of their even distribution through the box length have been picked as the evaluation criteria. The results of numerical modeling are described in picture 2.

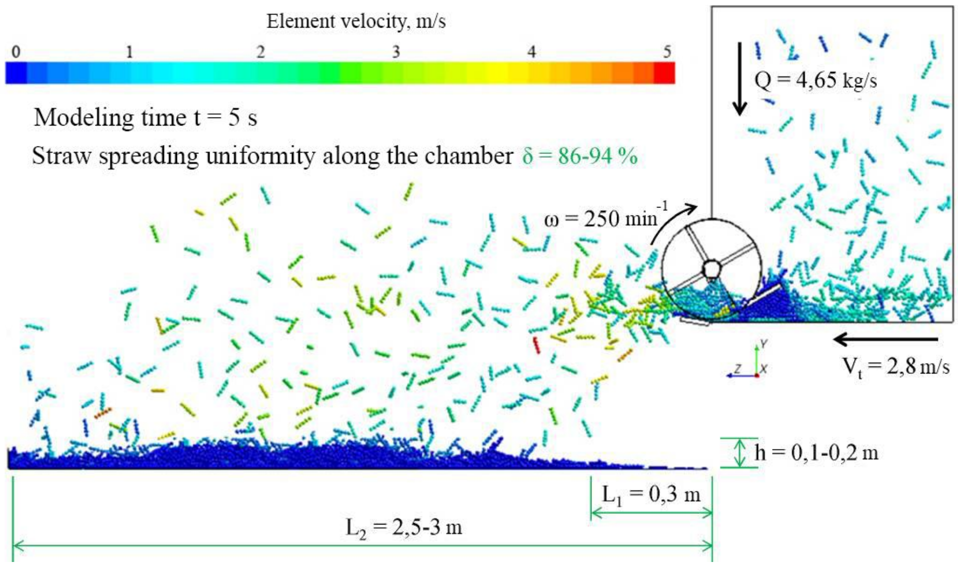

Fig. 2 – Process visualization of the rotor straw underlay spreading with condensing and guiding plates

3. The physical and mathematical model for the formation process of the pseudo-liquefied seed layer in the hydro-pneumatic seeding machine's intake chamber has been developed *(Boyko V.B., Aliyev E.B., 2015; Boyko V.B., Aliyev E.B., 2015)*.

Picture 3 displays the results as a graphical interpretation of the dynamic of the seed spreading in the intake chamber value.

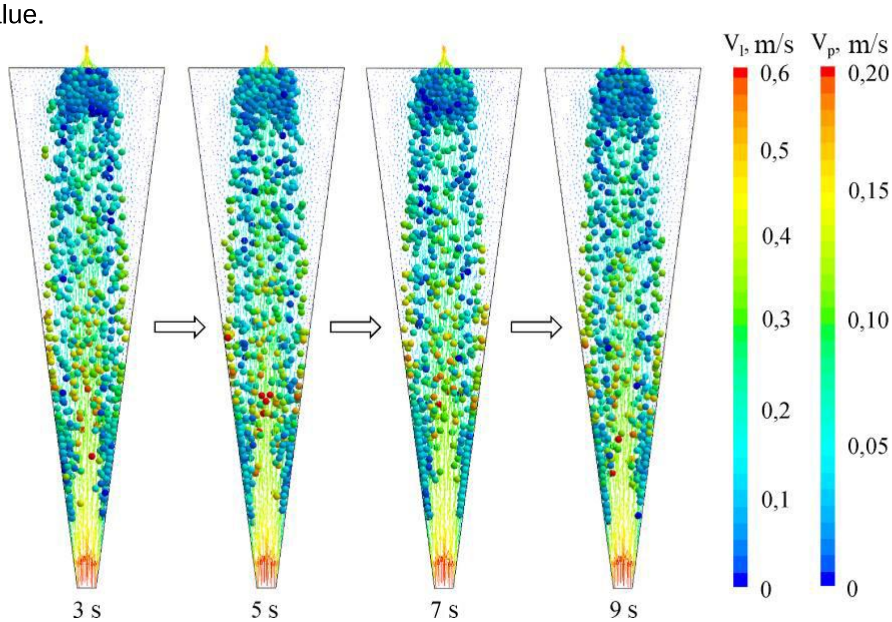

Fig. 3 – Visualization of the dynamic of the seed spreading in the hydro-pneumatic seeding machine's intake chamber value

4. As a result of theoretical researches there has been developed the physical and mathematical model for the process of the oil crops seeding material transferring with the air stream power and presented as visualization of this technological process, as described in picture 5 *(Aliyev E.B., Yaropud V.M., 2017; Aliyev E.B., 2017)*.

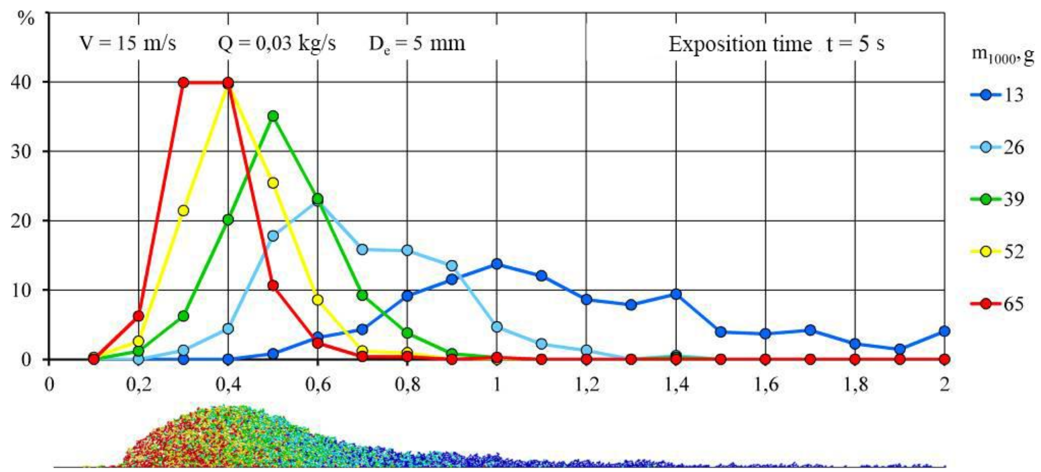

Fig. 4 – Visualization of the distribution of the seed fraction along the area length, which has been created by the air stream impact

5. Numerical modeling of the process of the milk-air mix movement in the milking machine has allowed us to determine a relation between the vacuum pressure fluctuation value and the milk withdrawal velocity, pulsation frequency and the working vacuum pressure value *(Linnik Yu.A., Aliyev E.B., Pavlenko S.I. 2014; Pavlenko S.I., Aliyev E.B., Linnik Yu.A., 2014)*.

Picture 5 describes the spreading of the 1-α liquid content along the milking machine milk hose by the upper milk pipe.

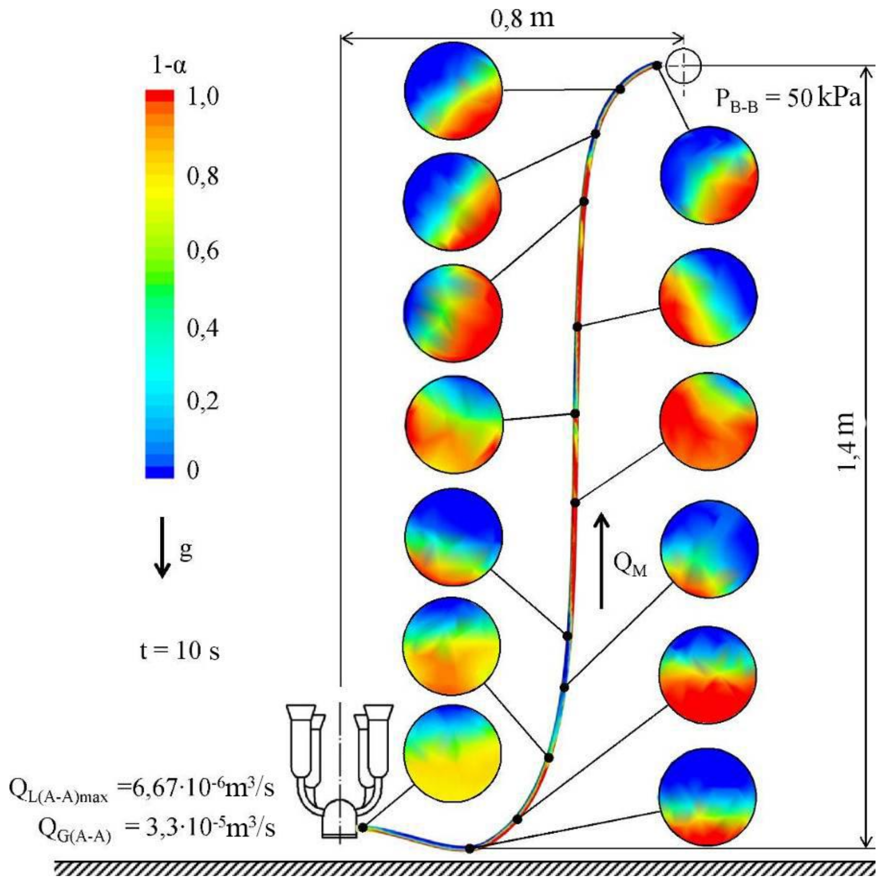

Fig. 5 – Spreading of the 1-α liquid content along the milking machine milk hose by the upper milk pipe

6. As a result of the working process numerical modeling for the photoelectronic seed separator executing mechanism, which consists of the falling cylinder and the inclined vibrating roll, there has been determined the timing diagram of the seed transportation in the separate vibration roll canal (picture 6).

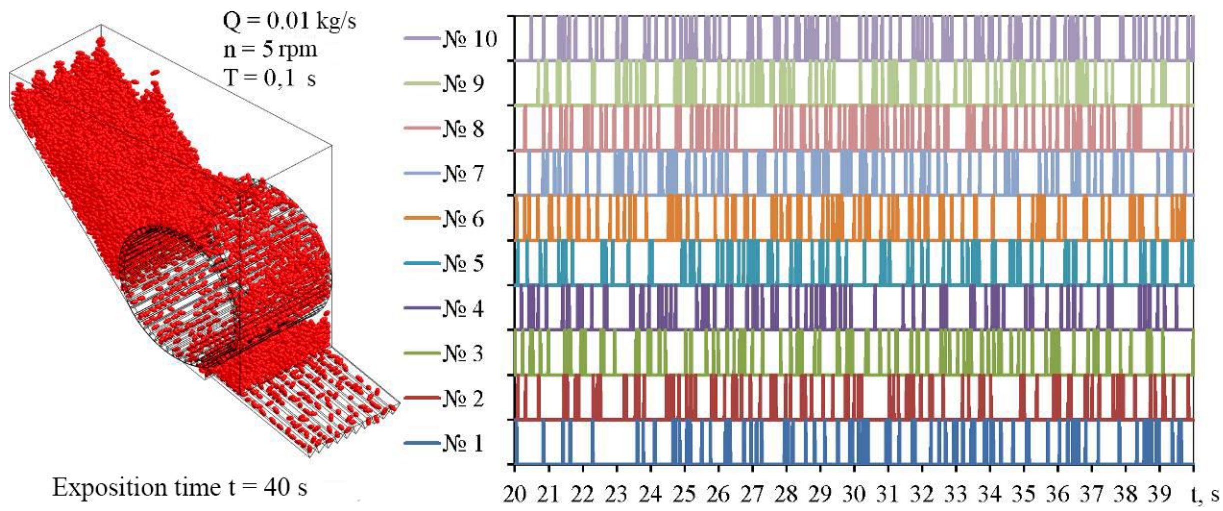

Fig. 6 – Timing diagram of the seed transportation in the separate vibration roll canal of the photoelectronic seed separator

7. Through the research on the technological process for the seed separation on the inclined vibrating plate (vibrating separator) in the Star CCM+ software it has become possible to determine the law of its spreading depending on the mass. Picture 7 describes the visualization of this technological process.

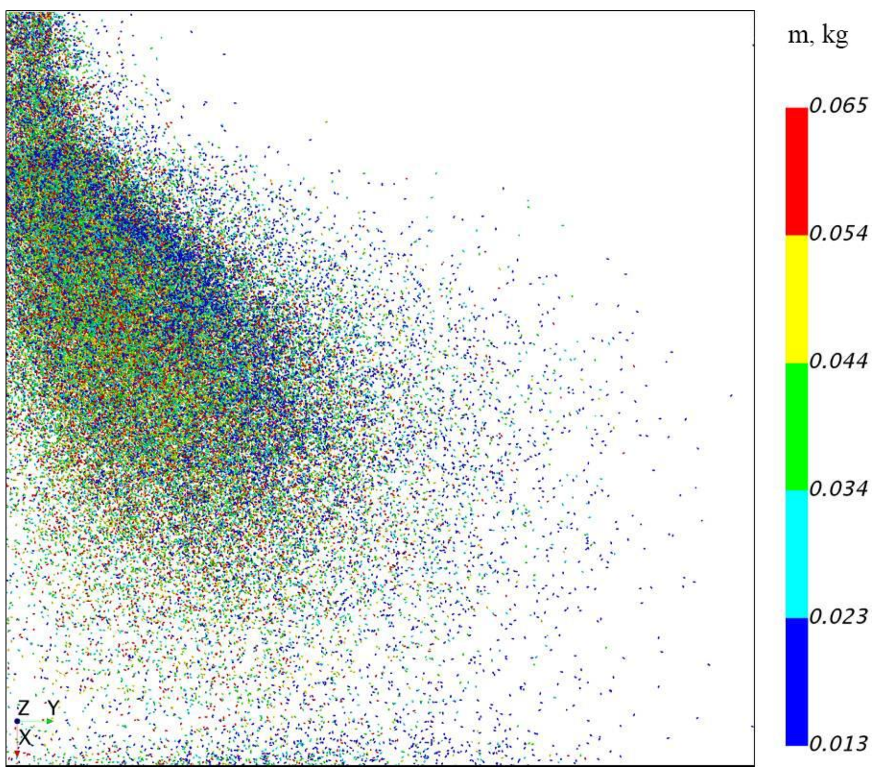

Fig. 7 – Visualization of the technological process of seed separation on the inclined vibrating plate (vibrating separator)

CONCLUSIONS

In this article are given the results of the numerical modeling within the Star CCM+ computer software for some mechanical and technological processes for agricultural manufacturing industry, as the mixing of components in a stream-type mixer-feeder, distribution of the straw underlay by the rotor spreader for the non-leash cow maintenance, formation of the pseudo-liquefied seed layer in the hydro-pneumatic seeding machine's intake chamber, transferring of the oil crops seeding material with the air stream power, functioning of the photoelectronic seed separator's executing mechanism, technological process of the seed separation on an inclined vibrating surface. These results point out the wide area of implementation of the numerical modeling for theoretical researches on mechanical and technological processes for agricultural manufacturing industry.

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