MODELING OF MOTION OF MATERIAL ON THE SURFACE OF SPIRAL ACTIVATOR IN BULK MATERIALS DRYER

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Summary. The model of motion of a particle on the spiral surface of activator in the new design dryer for granular materials is submitted in the article taking into account the interaction of the particle with the material.

Key words: dryer, activator, bulk material, model, interaction, trajectory.

INTRODUCTION

The construction of a dryer [1,7] with the cylindrical drying chamber (Fig.1) formed by outer cylindrical perforated wall and inner cylindrical perforated wall was suggested. Inner perforated wall is intended for supply of drying agent into the drying chamber. In the drying chamber spiral activators are mounted. The spiral activators intended for loosening and agitation of material during drying process.

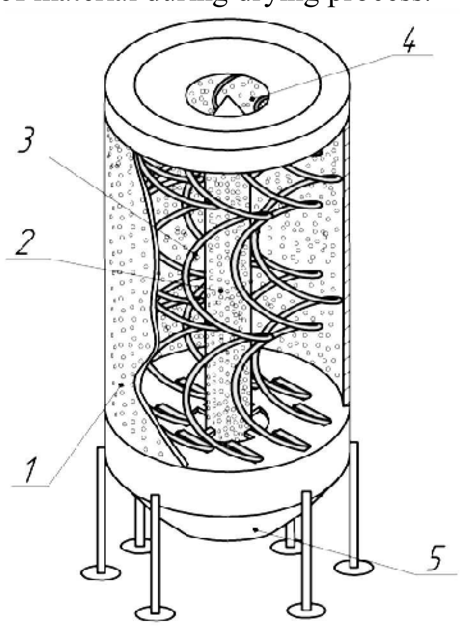

Fig.1. The drying chamber of the dryer:
1 – outer perforated wall of the drying chamber;
2 – inner perforated wall of the drying chamber for supplying of drying agent;
3 – spiral activators for loosening and agitation of material; 4 – loading section; 5 – unloading section

For grounding of the rational constructive and regime parameters of the spiral activators of the dryer it is necessary to study a motion of material on its surface.

ANALYSIS OF INVESTIGATIONS

A drying process of bulk materials was studied by Kotov B. I. [8], Lykov [9], Zelenko [10] and other scientists [11,14].

The researches dedicated to motion of materials on surfaces of operating devices were carried out by Vasylenko P.M. [15], Zaika P.M. [16] and others [18, 19].

But the process of moving of a particle on the surface of activator in the dryer of a new construction, with taking into account the interaction of the particle with the material, requires additional researches.

OBJECTIVE OF THE RESEARCH

The purpose of the research is to create a mathematical model that describes the movement of particles on the rough spiral surface of activator for loosening and mixing of the material in the new design dryer. The model will allow the rational regime parameters of this operational device to be determined.

RESULTS OF THE RESEARCH

Consider the shape of the spiral activator which is used in our dryer. The active surface (the surface of interaction with material) of the activator of the suggested construction dryer can be considered as a volumetric geometric figure formed by a circle with a center $o' - o'' - o'''$, moving in space along cylindrical helix (fig.2).

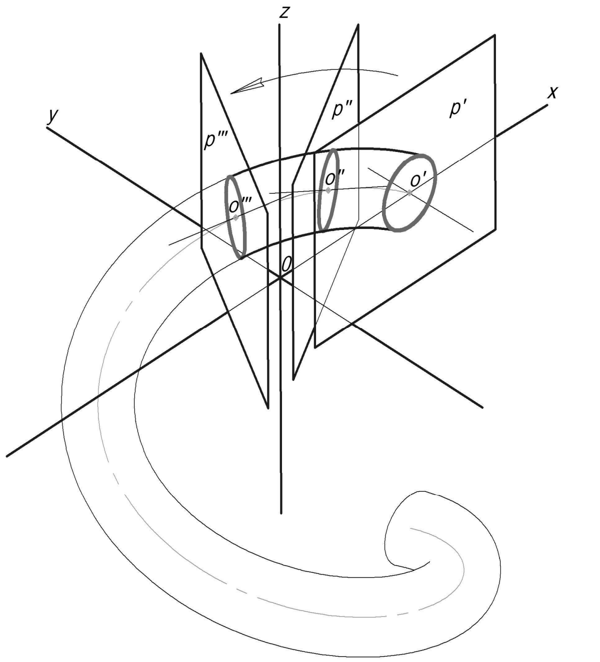

Fig.2. Forming of the surface of the activator by the circle with a center o

The equation, describing a shape of this surface (constraint equation), we can rationally introduce in the cylindrical coordinate system with radius r, angle α and coordinate z.

The equation of the spiral surface in the form $f = f(r,\alpha,z) = 0$ looks as follows:

$$z - \sqrt{r_{cn.}^2 - \left(R_{cn.} - r\right)^2} + \frac{\alpha \cdot k}{2 \cdot \pi} = 0, \quad (1)$$

where: R_{cn} - the radius of the spiral, m,

r_{cn} - the radius of the formative circle (a thickness of the coil), m;

k - the pitch of the helix, m.

The relative motion of a particle on the rough surface projected on the cylindrical coordinate system we can describe with a system of differential equations [15]:

$$\left.\begin{aligned}
& m\cdot(\ddot{r} - r\cdot\dot{\alpha}^2) = F_r + N\cdot\cos(\overline{e}_r,\overline{n}) - \\
& -\kappa\cdot|N|\cdot\frac{\dot{r}}{\sqrt{\dot{r}^2 + r^2\cdot\dot{\alpha}^2 + \dot{\zeta}^2}} + (-m\cdot w_{er}) + (-m\cdot w_{kr}), \\
& m\cdot(2\cdot\dot{r}\cdot\dot{\alpha} + r\cdot\ddot{\alpha}) = F_\alpha + N\cdot\cos(\overline{e}_\alpha,\overline{n}) - \\
& -\kappa\cdot|N|\cdot\frac{r\cdot\dot{\alpha}}{\sqrt{\dot{r}^2 + r^2\cdot\dot{\alpha}^2 + \dot{\zeta}^2}} + (-m\cdot w_{e\alpha}) + (-m\cdot w_{k\alpha}), \\
& m\cdot\ddot{\zeta} = F_\zeta + N\cdot\cos(\overline{e}_\zeta,\overline{n}) - \\
& -\kappa\cdot|N|\cdot\frac{\dot{\zeta}}{\sqrt{\dot{r}^2 + r^2\cdot\dot{\alpha}^2 + \dot{\zeta}^2}} + (-m\cdot w_{e\zeta}) + (-m\cdot w_{k\zeta}),
\end{aligned}\right\}, \quad (2)$$

where:

m - the mass of the particle, kg;

r, α and ζ - the coordinates of the relative motion of the particle, m;

κ - coefficient of friction of rough surface;

F_r, F_α and F_ζ - the projection of active forces on the axis of the moving coordinate system, N;

$\overline{e}_r$, $\overline{e}_\alpha$ and $\overline{e}_\zeta$ - unit vectors of the local coordinate basis, tangential to the coordinate lines r, α i ζ;

$\overline{n}$ - unit vector normal to the surface;

w_{er}, $w_{e\alpha}$ and $w_{e\zeta}$ - projections of acceleration of relative motion, m/s^2;

w_{kr}, $w_{k\alpha}$ and $w_{k\zeta}$ - projections of the Coriolis acceleration, m/s^2.

The value of the direction cosines of normal reactions $\cos(\overline{e}_r,\overline{n})$, $\cos(\overline{e}_\alpha,\overline{n})$ and $\cos(\overline{e}_\zeta,\overline{n})$, in the system (2) [15]:

$$\begin{aligned}
& \cos(\overline{e}_r,\overline{n}) = \cos(\overline{e}_r,\overline{e}_\xi)\cdot\cos(\overline{e}_\xi,n) + \\
& +\cos(\overline{e}_r,\overline{e}_\eta)\cdot\cos(\overline{e}_\eta,n) + \cos(\overline{e}_r,\overline{e}_\zeta)\cdot\cos(\overline{e}_\zeta,n),
\end{aligned} \quad (3)$$

$$\begin{aligned}
& \cos(\overline{e}_\alpha,\overline{n}) = \cos(\overline{e}_\alpha,\overline{e}_\xi)\cdot\cos(\overline{e}_\xi,n) + \\
& +\cos(\overline{e}_\alpha,\overline{e}_\eta)\cdot\cos(\overline{e}_\eta,n) + \cos(\overline{e}_\alpha,\overline{e}_\zeta)\cdot\cos(\overline{e}_\zeta,n),
\end{aligned} \quad (4)$$

$$\cos(\overline{e}_\varsigma,\overline{n}) = \cos(\overline{n},\overline{\zeta}), \quad (5)$$

where:

$$\left.\begin{aligned}
& \cos(\overline{e}_\xi,\overline{n}) = \cos(\overline{\xi},\overline{n}) = \frac{\dfrac{\partial f}{\partial \xi}}{\Delta f}, \\
& \cos(\overline{e}_\eta,\overline{n}) = \cos(\overline{\eta},\overline{n}) = \frac{\dfrac{\partial f}{\partial \eta}}{\Delta f}, \\
& \cos(\overline{e}_\zeta,\overline{n}) = \cos(\overline{\varsigma},\overline{n}) = \frac{\dfrac{\partial f}{\partial \varsigma}}{\Delta f},
\end{aligned}\right\}, \quad (6)$$

and:

$$\cos(\overline{e}_r,\overline{e}_\xi) = \frac{\xi}{r} = \cos(\alpha), \quad (7)$$

$$\cos(\overline{e}_r,\overline{e}_\eta) = \frac{\eta}{r} = \sin(\alpha), \quad (8)$$

$$\cos(\overline{e}_r,\overline{e}_\zeta) = 0, \quad (9)$$

$$\cos(\overline{e}_\alpha,\overline{e}_\xi) = -\sin\alpha, \quad (10)$$

$$\cos(\overline{e}_\alpha,\overline{e}_\eta) = \cos\alpha, \quad (11)$$

$$\cos(\overline{e}_\alpha,\overline{e}_\zeta) = 0. \quad (12)$$

In (6) $\Delta f = \sqrt{\left(\frac{\partial f}{\partial x}\right)^2 + \left(\frac{\partial f}{\partial y}\right)^2 + \left(\frac{\partial f}{\partial z}\right)^2}$, is the modulus of the gradient.

After substitution (6-12) in (3-5), taking into account following equations, describing relations between Cartesian and Cylindrical coordinates:

$$\left.\begin{aligned} \xi &= r\cdot\cos(\alpha), \\ \eta &= r\cdot\sin(\alpha), \\ \zeta &= \zeta, \end{aligned}\right\}, \tag{13}$$

we obtain:

$$\cos(\overline{e}_r,\overline{n}) = \frac{4\cdot\pi\cdot r\cdot(R_{cn}-r)}{\sqrt{r_{cn}^2-(R_{cn}-r)^2}\cdot\sqrt{k^2+\dfrac{4\cdot\pi^2\cdot r^2\cdot r_{cn}^2}{r_{cn}^2-(R_{cn}-r)^2}}}, \tag{14}$$

$$\cos(\overline{e}_\alpha,\overline{n}) = \frac{2\cdot k}{\sqrt{k^2+\dfrac{4\cdot\pi^2\cdot r^2\cdot r_{cn}^2}{r_{cn}^2-(R_{cn}-r)^2}}}, \tag{15}$$

$$\cos(\overline{e}_\zeta,\overline{n}) = \frac{4\cdot\pi\cdot r}{\sqrt{k^2+\dfrac{4\cdot\pi^2\cdot r^2\cdot r_{cn}^2}{r_{cn}^2-(R_{cn}-r)^2}}}, \tag{16}$$

The acceleration of translational motion w_e, assuming that the beginning of stationary and moving coordinate systems lie at the one point, $z=\zeta$ and rotation of the moving coordinate system around the axis z is with a constant angular velocity:

$$w_e = r\cdot\omega_e^2, \tag{17}$$

where: ω_e - angular velocity of rotation of the operating device, rad/s.

Projected on the tangent to the coordinate lines:

$$\left.\begin{aligned} w_{er} &= r\cdot\omega_e^2, \\ w_{e\alpha} &= 0, \\ w_{e\zeta} &= 0, \end{aligned}\right\}. \tag{18}$$

Coriolis acceleration:

$$\left.\begin{aligned} w_{kr} &= -2\cdot\omega_e\cdot r\cdot\dot{\alpha}, \\ w_{k\alpha} &= 2\cdot\omega_e\cdot\dot{r}, \\ w_{k\zeta} &= 0, \end{aligned}\right\}. \tag{19}$$

Consider the projection of the active forces F_r, F_α and F_ζ on axes r, α and ζ, which influence on the particle.

The force of gravity $m\cdot g$ is applied to the particle with mass m that directed in the opposite direction to the coordinate axis ζ:

$$F_{тяж.} = -m\cdot g. \tag{20}$$

A particle in the bulk material environment constantly interacts with other particles of the material. It causes the nature of the movement of the particle. So we can't consider the motion of the particle without taking into account its interaction with other particles.

Mixing of bulk material is a highly complex process. The nature of the movement of particles in the bulk material environment depends on many factors, including material properties, design and operational parameters of the operating devices of machines and is difficult to describe. The theory, associated with mixing of loose environment is quite weak and is mainly based on empirical and experimental dependences of coefficients, established for individual materials in their interaction with specific operating devices.

Aiming to study the impact of the design and the operational parameters of the operating device on the intensity of loosening and mixing of material by means of determination the influence of these parameters on the nature of the trajectory of the particles, we considering the interaction of particles with the bulk material with some approximation and with the following assumptions:

- at any time the particle in the bulk material contacts simultaneously with *n* other particles of the material. Number of particles *n* is inconsistent over time and varies in a certain range. A minimum and maximum number of particles depend on the shape of the particles, their orientation in space, bulk density of the material and other factors;
- the forces, applied to the particle, as a result of its interaction with other particles of the material are considered as the resultant force which is equal to the vector sum of these forces. The quantity and the direction of the force are considered as random variable that varies in time in certain intervals;
- the vector of the resultant force of interaction with the material lies on a plane, tangent to the spiral surface, at the point of its contact with the underlying particle. We consider only the tangent component of the force, projected on the tangent plane to the surface at the point of contact with the particle.

Perpendicular to the plane component of the force is balanced by the normal reaction N;

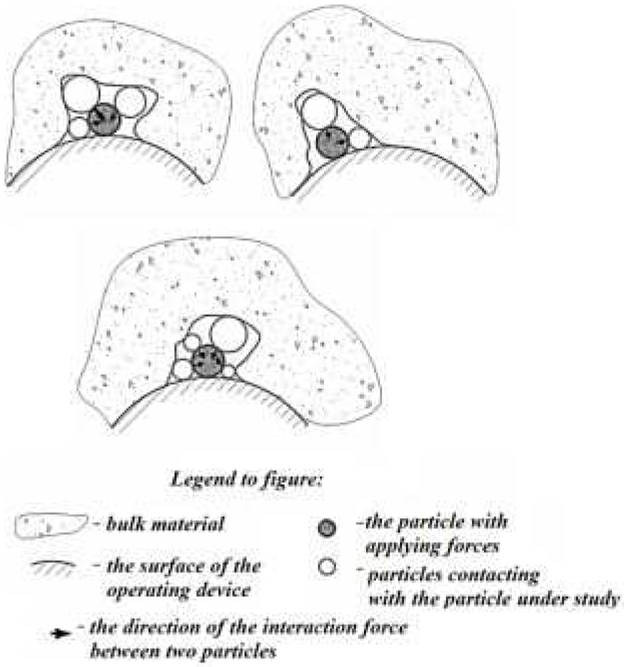

Fig.3. Schematic representation of the possible interactions of material particles on the surface of operating device

- the value of the resultant force varies from 0 to some maximum value that depends on the properties of the material, conditions and regimes of operation of the dryer.

The accuracy of the model will be determined by correctness of applied maximum resultant force and the nature of variability of its value and direction according to the actual conditions.

The interaction force:

$$\overline{F}_{\text{вз.}} = \overline{F}^{\tau}_{\text{вз.}} + \overline{F}^{n}_{\text{вз.}}. \qquad (21)$$

Taking into account the aspect that the normal component of the resultant force $\overline{F}^{n}_{\text{вз.}}$ is balanced by the normal reaction of the surface N, it is sufficient to specify the tangential component projection of the force $\overline{F}^{\tau}_{\text{вз.}}$ on the axes r, α and ζ without consideration of its normal component.

$\overline{F}^{\tau}_{\text{вз.}}$ lies in the plane *T*, tangent to the curved surface at the point of contact with the particle (fig.4).

Consider the tangential component of the force of particle interaction with the material $\overline{F}^{\tau}_{\text{вз.}}$, which lies in the plane T.

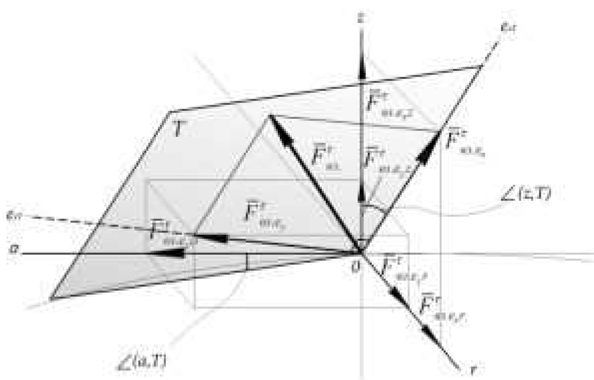

Fig.4. The tangential component of the particle interaction force on the surface of the operating device and its projection on cylindrical coordinates r, α and ζ

To set the direction of this force, we apply a local rectangular coordinate basis on the plane T with axes unit vectors $\overline{e}_{x'\tau}, \overline{e}_{y'\tau}$ and the point of reference O which is a point of contact of the particle with the surface. Place one of the unit vectors $\overline{e}_{x'\tau}$ in the tangent to axes r, z surface, so:

$$\overline{F}^{\tau}_{\text{вз.}} = \overline{F}^{\tau}_{\text{вз.}x'} + \overline{F}^{\tau}_{\text{вз.}y'} \qquad (22)$$

$$\left|\overline{F}^{\tau}_{\text{вз.}}\right| = \sqrt{\left|\overline{F}^{\tau}_{\text{вз.}x'}\right|^2 + \left|\overline{F}^{\tau}_{\text{вз.}y'}\right|^2}. \qquad (23)$$

Tangential component of the force of interaction $\overline{F}^{\tau}_{\text{вз.}}$ and its projections on coordinates with the unit vectors $\overline{e}_{x'\tau}$ and $\overline{e}_{y'\tau}$ we define in the following order:

$$\left|\overline{F}^{\tau}_{\text{вз.}}\right| = rand\left[0, \left|\overline{F}^{\tau}_{\text{вз.}\max}\right|\right], \qquad (24)$$

$$\pm\overline{F}^{\tau}_{\text{вз.}x'} = rand\left[0, \left|\overline{F}^{\tau}_{\text{вз.}}\right|\right], \qquad (25)$$

$$\pm\overline{F}^{\tau}_{\text{вз.}y'} = \sqrt{\left|\overline{F}^{\tau\,2}_{\text{вз.}}\right| - \left|\overline{F}^{\tau\,2}_{\text{вз.}x'}\right|}, \qquad (26)$$

where: $rand[a,b]$ – simulated random value of the particle-material interaction force. It is generated with a certain periodicity in the range of numbers from the minimum a to the maximum b.

The sign «±» means that the forces can be applied in the forward and in the opposite direction relatively to the coordinate unit vectors $\overline{e}_{x'\tau}$

and $\overline{e}_{y'\tau}$ of the local coordinate basis on the tangent plane.

The projections $\overline{F}^{\tau}_{вз.x'}$ and $\overline{F}^{\tau}_{вз.y'}$ of tangential component of the force $\overline{F}^{\tau}_{вз.}$ on the tangent to the coordinate lines r, α and ζ of cylindrical coordinate system:

$$\left.\begin{aligned} \overline{F}^{\tau}_{вз.r} &= \overline{F}^{\tau}_{вз.x'r} + \overline{F}^{\tau}_{вз.y'r} = \\ &= \overline{F}^{\tau}_{вз.x'} \cdot \cos(\overline{e}_{x'\tau}, \overline{e}_r) + \overline{F}^{\tau}_{вз.y'} \cdot \cos(\overline{e}_r, \overline{e}_{y'\tau}), \\ \overline{F}^{\tau}_{вз.\alpha} &= \overline{F}^{\tau}_{вз.x'\alpha} + \overline{F}^{\tau}_{вз.y'\alpha} = \\ &= \overline{F}^{\tau}_{вз.x'} \cdot \cos(\overline{e}_{\alpha}, \overline{e}_{x'\tau}) + \overline{F}^{\tau}_{вз.y'} \cdot \cos(\overline{e}_{\alpha}, \overline{e}_{y'\tau}), \\ \overline{F}^{\tau}_{вз.\zeta} &= \overline{F}^{\tau}_{вз.x'\zeta} + \overline{F}^{\tau}_{вз.y'\zeta} = \\ &= \overline{F}^{\tau}_{вз.x'} \cdot \cos(\overline{e}_{x'\tau}, \overline{e}_{\zeta}) + \overline{F}^{\tau}_{вз.y'} \cdot \cos(\overline{e}_{y'\tau}, \overline{e}_{\zeta}). \end{aligned}\right\}. \quad (27)$$

For projecting of the components $\overline{F}^{\tau}_{вз.e_{x\tau}}$ and $\overline{F}^{\tau}_{вз.e_{y\tau}}$ of the force on tangents to the coordinate lines r, α and ζ it is necessary to determine the values of the angles $\angle(\overline{e}_r, \overline{e}_{x'\tau})$, $\angle(\overline{e}_r, \overline{e}_{y'\tau})$, $\angle(\overline{e}_{\alpha}, \overline{e}_{x'\tau})$, $\angle(\overline{e}_{\alpha}, \overline{e}_{y'\tau})$ $\angle(\overline{e}_{\zeta}, \overline{e}_{x'\tau})$ and $\angle(\overline{e}_{\zeta}, \overline{e}_{y'\tau})$.

$\angle(\overline{e}_{\alpha}, \overline{e}_{x'\tau}) = 0$ - considering that the component of the resultant force $\overline{F}^{\tau}_{вз.x'}$ lies in the plane $r\zeta$.

Determine the values of angles $\angle(r, \overline{e}_{x'\tau})$ and $\angle(\overline{e}_{\zeta}, \overline{e}_{x'\tau})$. Consider the equation of the surface (1) with a fixed value α (fig.5). Then function takes the form $\zeta = f(r)$ and describes a circle on the plane $r\zeta$ formed by intersection of spiral volumetric surface (1) by this surface.

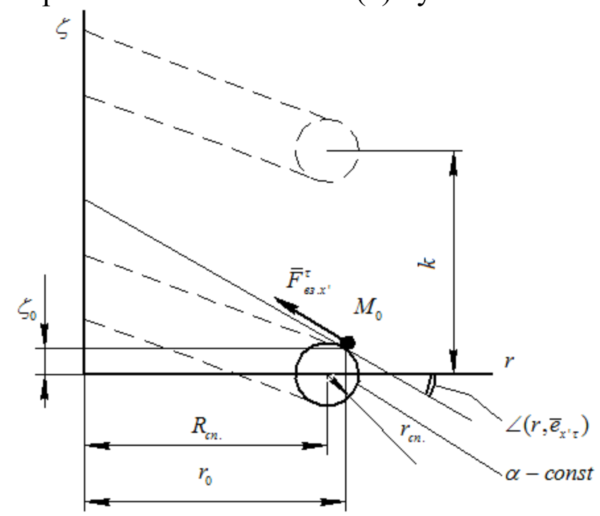

Fig.5. The determination of the angles $\angle(\overline{e}_r, \overline{e}_{x'\tau})$ and $\angle(\overline{e}_{\zeta}, \overline{e}_{x'\tau})$

The value of the angle for our function $\zeta = f(r)$ can be found by the formula [20]:

$$tg(\overline{e}_r, \overline{e}_{x'\tau}) = \frac{df}{dr}. \quad (28)$$

Then:

$$\begin{aligned} \angle(\overline{e}_r, \overline{e}_{x'\tau}) &= 90^{\circ} - \angle(\zeta, \overline{e}_{x'\tau}) = \\ &= arctg\left(\frac{R_{cn} - r}{\sqrt{{r_{cn}}^2 - (R_{cn} - r)^2}}\right). \end{aligned} \quad (29)$$

The values of the angles $\angle(\overline{e}_r, \overline{e}_{y'\tau})$, $\angle(\overline{e}_{\alpha}, \overline{e}_{y'\tau})$ and $\angle(\overline{e}_{\zeta}, \overline{e}_{y'\tau})$ we can find by the known cosines of the angles $\cos(\overline{e}_r, \overline{n})$, $\cos(\overline{e}_{\alpha}, \overline{n})$ and $\cos(\overline{e}_{\zeta}, \overline{n})$, (21-23) between the normal to the surface and the tangent to the coordinate lines r, α and ζ (fig.6):

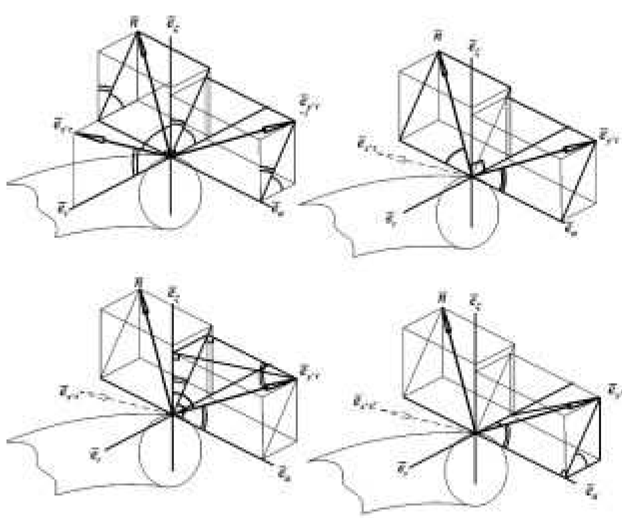

Fig.6. The determination of the angles $\angle(\overline{e}_r, \overline{e}_{y'\tau})$, $\angle(\overline{e}_{\alpha}, \overline{e}_{y'\tau})$ i $\angle(\overline{e}_{\zeta}, \overline{e}_{y'\tau})$

$$\angle(\overline{e}_{\alpha}, \overline{e}_{y'\tau}) = 90^{\circ} - \angle(\overline{e}_{\alpha}, \overline{n}), \quad (30)$$

$$\cos(\overline{e}_{\zeta}, \overline{e}_{y'\tau}) = \cos(\overline{e}_{\alpha}, \overline{n}) \cdot \cos(\overline{e}_{\zeta}, \overline{e}_{x'\tau}), \quad (31)$$

and:

$$\cos(\overline{e}_r, \overline{e}_{y'\tau}) = \cos(\overline{e}_{\alpha}, \overline{n}) \cdot \cos(\overline{e}_{x'\tau}, \overline{e}_{\zeta}). \quad (32)$$

Result projections of forces on tangential to coordinate lines:

$$\left.\begin{aligned} F_r &= \overline{F}^{\tau}_{r.вз.} \\ F_{\alpha} &= \overline{F}^{\tau}_{\alpha.вз.} \\ F_{\zeta} &= -m \cdot g + \overline{F}^{\tau}_{\zeta.вз.} \end{aligned}\right\}. \quad (33)$$

Substituting (14-20) into (2) and attaching equation (1) we obtain the system:

$$\left.\begin{aligned}
&m\cdot(\ddot{r}-r\cdot\dot{\alpha}^2)=\bar{F}^{\tau}_{r.в з.}-\\
&-N\cdot\frac{4\cdot\pi\cdot r\cdot(R_{сп}-r)}{\sqrt{r_{сп}{}^2-(R_{сп}-r)^2}\cdot\sqrt{k^2+\dfrac{4\cdot\pi^2\cdot r^2\cdot r_{сп}{}^2}{r_{сп}{}^2-(R_{сп}-r)^2}}}-\\
&-\kappa\cdot|N|\cdot\frac{\dot{r}}{\sqrt{\dot{r}^2+r^2\cdot\dot{\alpha}^2+\dot{\zeta}^2}}-\\
&-m\cdot(r\cdot\omega_e^2-2\cdot\omega_e\cdot r\cdot\dot{\alpha}),\\
&m\cdot(2\cdot\dot{r}\cdot\dot{\alpha}+r\cdot\ddot{\alpha})=\bar{F}^{\tau}_{\alpha.вз.}+\\
&+N\cdot\frac{2\cdot k}{\sqrt{k^2+\dfrac{4\cdot\pi^2\cdot r^2\cdot r_{сп}{}^2}{r_{сп}{}^2-(R_{сп}-r)^2}}}-\\
&-\kappa\cdot|N|\cdot\frac{r\cdot\dot{\alpha}}{\sqrt{\dot{r}^2+r^2\cdot\dot{\alpha}^2+\dot{\zeta}^2}}-m\cdot 2\cdot\omega_e\cdot\dot{r},\\
&m\cdot\ddot{\zeta}=-m\cdot g+\bar{F}^{\tau}_{z.вз.}+\\
&+N\cdot\frac{4\cdot\pi\cdot r}{\sqrt{k^2+\dfrac{4\cdot\pi^2\cdot r^2\cdot r_{сп}{}^2}{r_{сп}{}^2-(R_{сп}-r)^2}}}-\\
&-\kappa\cdot|N|\cdot\frac{\dot{\zeta}}{\sqrt{\dot{r}^2+r^2\cdot\dot{\alpha}^2+\dot{\zeta}^2}},\\
&\zeta-\sqrt{r_{сп.}^2-\left(R_{сп.}-r\right)^2}+\frac{\alpha\cdot k}{2\cdot\pi}=0.
\end{aligned}\right\}.$$

(34)

The system (34) consists of four equations containing three unknown coordinates, its first and second time derivatives, and the unknown normal reaction N. Taking into account (24-33), in the case of interaction of particles with the material, it can be solved using numerical methods.

CONCLUSIONS

The mathematical model, describing the motion of a particle on the rough surface of spiral activator of the considered dryer, is submitted. The model takes into account the interaction of a particle with surrounding bulk material. The obtained model allows the impact of various factors on the motion of the particles of bulk material to be analyzed and the rational regime and structural parameters of spiral activator, designed for loosening and mixing of material during drying, to be determined.

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