The force analysis of interaction of furnace charge layer with working body of vibration feeder for sintering machine charging

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Abstract
For change of drum feeders for laying of furnace charge to the sintering belt by vibrational ones providing laying of layer with the specified thickness and profile, regularities of layer motion relating to the bottom of charging device are considered and expressions for calculation of forces affecting in the contact of layer with its bound elements of vibrating feeder are developed. On this basis, the conclusion on possibility of electric power costs reduction in case of layer blowing and improvement of agglomerate quality is drawn.
Power analysis opens the potential of further improvement of charge unit of agglomerative machines providing formation of layer with specified geometry and profile.
Key words: CHARGING DEVICE AGGLOMERATIVE MACHINES, VIBRATIONAL FEEDER, SINTER BURDEN LAYER, INTERACTION OF LAYER WITH THE BOTTOM, FORCES IN A LAYER, LAYING OF FURNACE CHARGE, ELECTRIC POWER COSTS, QUALITY OF AGGLOMERATE

One of methods of improvement of agglomerative factories is change of drum feeders for laying of furnace charge to the sintering belt by vibrational feeders allowing formation of efficient profile of layer in sintering belt providing decrease in gas-dynamic impedance during furnace charge layer blowing in the course of its agglomeration.

Formation of layer in the charging device takes place due to forces affecting in the layer and its contact with the bottom and walls of vibrating feeder.

The charging device (vibrating feeder of special design) is installed under the tap hole of charge hopper blocking its section completely; this provides smooth charging of sintering belt with the specified layer profile without arch formation and hanging.

Such charging devices can form any profile of layer surface in sintering belt and efficient distribution of particles size in the layer thickness providing saving of the electric power layer blowing and improvement of agglomerate quality due to reduction of content of class (-5) mm in shattered agglomerate.

The bucket of the charging device can execute the following types of vibrations depending on their trajectories:

- rectilinear vibrations, at an angle to the load-carrying plane, uniform (identical to all points of bucket along its length);
- circular uniform vibrations, each point of bucket race out circular trajectory (in the specific case - elliptic);
- elliptic non-uniform vibrations, each point of bucket executes vibrations along its length with the trajectory (linear or elliptic) with parameters (big axis of ellipse and angles of its slope) changing along the bucket length.

Let us consider forces affecting the layer of material moving in the bottom of charging device tilted at an angle α to the horizon. Let us consider a case when the bucket executes rectilinear vibrations which direction makes an angle β with its bottom.

The equations of movement of material layer relating to the bottom of charging device are of the following form:

$$\begin{aligned} m\ddot{X} &= P\sin\alpha + I_h + F_B + F_{s.h.} \\ m\ddot{Y} &= P\cos\alpha + I_v + N + F_{s.v.} \end{aligned}, \qquad (1)$$

where m – the specified mass of layer [1]; I_h, I_v - projections of forces of inertia to the axes OX and OY, P — gravity force; N — normal reaction of bucket or underlying layer to overlying layer of material; F_B - friction force of material on the bottom of bucket or underlying layer of material; $F_{s.h.}$, $F_{s.v.}$ - material friction force projections on side surfaces (walls) of bucket to the axes OX and OY.

Normal reaction N and friction force F_B are determined for the bucket bottom plane (or planes parallel to the bottom), gravity and inertia are determined for the whole volume of material, and friction force on walls is determined by height of all layer. Relative accelerations $\ddot{X}$ and $\ddot{Y}$ are determined as average accelerations of layer.

In case of solution of the similar task for unit load, normal reaction and friction force on the bottom of bucket are determined from condition that unit load moves together with bucket for some time, i.e. $Y=0$ and $X=0$. The movement equations turn into balance equations, in which the left parts are set to zero and expressions for determination of N and F_B are found. At that, forces of side friction are absent.

Such assumption would be incorrect for material layer; even without frictional sliding of material on the bottom, the upper layers of material move according to the law different from the law of bucket vibration.

According to [1, 2], let us accept the assumption on consideration of all the internal interactions in a layer by coefficients of vibrations damping throughout its height. Under condition of absence of material frictional sliding on the bottom or material separation from vibrating plane, the vertical component of absolute acceleration of material in the point at height h will be equal to $A\omega^2 \cdot e^{-\gamma_v h} \cdot \sin\beta_T \cdot \sin\omega t$, and horizontal component will be equal to $A\omega^2 \cdot e^{-\gamma_h h} \cdot \cos\beta_T \cdot \cos\omega t$, where A – amplitude, ω – vibration frequency of bucket, β_T – slope angle of rectilinear trajectory of point to the bucket plane, γ_v, γ_h – coefficients of damping of plane stress waves of compression and shift throughout the layer height.

Relative specific (on height unit) acceleration of layer with height of N in periods when there is no sliding and separation:

$$\ddot{X} = \frac{1}{H-h} \cdot A\omega^2 \cdot \cos\beta_T \cdot \cos\omega t \int_h^H \left(e^{-\gamma_h h} - 1\right) dh$$
$$\ddot{Y} = \frac{1}{H-h} \cdot A\omega^2 \cdot \sin\beta_T \cdot \sin\omega t \int_h^H \left(e^{-\gamma_v h} - 1\right) dh \qquad (2)$$

Inertia force for material will be determined by acceleration of translation:

$$I_v = mA\omega^2 \sin\beta_T \sin\omega t;$$
$$I_h = mA\omega^2 \cos\beta_T \sin\omega t;, \qquad (3)$$

Having substituted expressions (2) and (3) into the equations of movement (1), we obtain the equations for determination of normal reaction and friction force on bottom:

$$N + F_{s.v.} = mg\cos\alpha - \frac{mA\omega^2}{(H-h)\beta_V} \sin\beta_T \cdot \sin\omega t (e^{-\gamma_h h} - e^{-\gamma_h H}) + F_B + F_{s.v.}, \qquad (4)$$

Normal reaction of the bottom or layer of material to overlying layer is function of gravity force of material, its mechanical properties, amplitudes, vibration frequencies, angle of vibrations and coefficient of vertical vibrations damping.

Friction forces on walls of bucket and normal reaction to the bottom depend on bucket width. At that, the direction of friction forces on walls depends on the bucket wall, weather it moves together with the bottom or is motionless. If the walls of bucket are motionless, specific friction force on walls at layer height h is equal to:

$$F_{s.sp.} = 2f_1 n \frac{N(h)}{B}, \qquad (5)$$

where $N(h)$ - normal reaction of plane parallel to the bucket bottom at height h, f_1 - coefficient of layer friction on bucket walls, B – the layer width equal to bucket width.

The coefficient of side pressure n is determined by a formula: [2]

$$n = \frac{1}{1 + 2f^2 + 2\sqrt{(1+f^2)(f^2 - f_1^2)}}, \qquad (6)$$

where f - coefficient of internal friction of material.

The angle β_T made by friction force on bucket walls is changed with the layer height as horizontal and vertical components of this force are reduced unequally for longitudinal and cross waves of compression and shift due to inequality of coefficients of these waves damping.

$$tg\beta_T = \frac{\sin\beta \cdot e^{-\gamma_v h}}{\cos\beta \cdot e^{-\gamma_h h}}, \qquad (7)$$

The complete frictional force on walls emerging in unit of bucket length and walls is determined as integral variable value along the layer height of specific frictional force:

$$F_{s.v.} = 2N\int_h^H f_1 \frac{n}{B} dh, \qquad (8)$$

Material gravity force in bucket length unit is:

$$mg = (H-h)B\gamma, \qquad (9)$$

where γ – bulk density of furnace charge.

The directions of bucket acceleration are determined by expression $\sin\omega t$, i.e. for values $\omega t = 0 \div \pi$ acceleration is positive, and for values $\omega t = \pi \div 2\pi$, it is negative. Friction force on walls changes a sign at other moments of vibration cycle. For example, in case of forward-upward movement of working body, i.e. at

$$\omega t = -\frac{\pi}{2} \div \frac{\pi}{2},$$

the force F_s is negative, and at

$$\omega t = \frac{\pi}{2} \div \frac{3}{2}\pi,$$

it is positive.

Normal reaction for interval

$\omega t = -\frac{\pi}{2} \div \frac{\pi}{2}$ is determined by expression:

$$N = \frac{B\gamma\cos\alpha}{a}\cdot(e^{a(H-h)}-1)+\frac{B\gamma A\omega^2\sin\beta_T\sin\omega t}{g(a-\beta_v)}\left[e^{-\gamma_v h}-e^{-a(H-h)-\gamma_v H}\right], \tag{10}$$

where $a=\dfrac{2fn\cdot\sin\beta_T}{B}$.

We obtain vertical projection of friction force of material on bucket walls with the use of expression (8).

For an interval $\omega t=-\dfrac{\pi}{2}\div\dfrac{\pi}{2}$:

$$F_{s.v.}=\frac{B\gamma\cos\alpha}{a}\left[e^{a(H-h)}-1-a(H-h)\right]+\frac{B\gamma A\omega^2\sin\beta_T\cdot\sin\omega t}{g(a-\beta_v)}\begin{bmatrix}\dfrac{a}{\beta_v}e^{-\gamma_v h}-\dfrac{a-\beta_v}{\beta_v}e^{\gamma_v H}-\\-e^{a(H-h)-\gamma_h H}\end{bmatrix}, \tag{11}$$

For an interval $\omega t=\dfrac{\pi}{2}\div\dfrac{3}{2}\pi$ we obtain:

$$N=-\frac{B\gamma\cos\alpha}{a}(e^{-a(H-h)}-1)-\frac{B\gamma A\omega^2\sin\beta_T\sin\omega t}{g(a-\beta_v)}(e^{-\beta_v h}-e^{-a(H-h)-\beta_v H}), \tag{12}$$

$$F_{s.v.}=\frac{B\gamma\cos\alpha}{a}\left[e^{-a(H-h)}-1+a(H-h)\right]+\frac{B\gamma A\omega^2\sin\beta_T\cdot\sin\omega t}{g(a+\beta_v)}\begin{bmatrix}-\dfrac{a}{\beta_B}e^{-\beta_v h}+\dfrac{a+\beta_B}{\beta_a}e^{-\beta_v H}-\\-e^{-a(H-h)-\beta_v H}\end{bmatrix} \tag{13}$$

In expressions (10-13), $\sin\beta_T$ the average value of angle of vibration along layer thickness is

$$\sin\beta_{T.av}=\frac{1}{H-h}\int_h^H\sin\left[arctg(tg\beta_T\cdot e^{h(\beta_z-\beta_B)})\right]dh=\frac{1}{(H-h)(\beta_z-\beta_B)}\times$$
$$\times\ln tg\left(\frac{\pi}{4}-\frac{arctg(tg\beta_T\cdot e^{H(\beta_z-\beta_B)})}{2}\right)-\ln tg\left(\frac{\pi}{4}+\frac{arctg(tg\beta_T\cdot e^{h(\beta_z-\beta_B)})}{2}\right), \tag{14}$$

Friction force of material on the bottom of bucket or on the surface parallel to the bottom is

$$F_B=-\gamma B(H-h)\sin\alpha-\frac{\gamma B}{g\beta}A\omega^2\cos\beta_T\cdot\sin\omega t(e^{-\beta_h h}-e^{-\beta_h H})\pm\frac{F_{s.v}(\beta_h-\beta_v)(H-h)}{tg\beta_T\left[e^{(\beta_h-\beta_v)H}-e^{(\beta_h-\beta_v)h}\right]}, \tag{15}$$

The upper signs correspond to the intervals $\omega t=-\dfrac{\pi}{2}\div\dfrac{\pi}{2}$, lower ones correspond to intervals $\omega t=\dfrac{\pi}{2}\div\dfrac{3}{2}\pi$.

Conclusions

The expressions determining affecting forces in bulk layer (agglomerative furnace charge) in the course of its charging in sintering belt are obtained. Application of the obtained expressions for forces affecting in the layer and its contact with bottom and walls of charging bucket allows setting of kinematic and geometrical parameters of bucket providing laying of furnace charge layer of specified height and profile of section. Therefore, electric power costs in case of layer blowing at its agglomeration are reduced and the quality of agglomerate is increased due to reduction content of fraction (-5 mm).

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