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3 RESEARCH OF TECHNICAL SYSTEMS OF MATERIALS SORTING PROCESSES

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ABSTRACT

The studies carried out revealed the influence of the vibration frequency and the angle of inclination on the efficiency of sorting. It was found that with an increase in the vibration frequency and vibration amplitude of the box, the separation of the material and the sorting speed increase. The proposed model made it possible to determine the transport speed in the case when the sieve screen carries out a circulating movement, which is the application of two independent vibrations with different amplitudes and frequencies. The number of throws of the material to be sorted is influenced by the transport time of this material over the surface of the sieve and the amount of vibration excitation to this material. The dependence of the used power on the design and technological parameters of the vibration screen was revealed. An algorithm and method for calculating the main parameters of a vibration screen were developed.

KEYWORDS

Vibration screen, material, sorting, grain composition, physical, mathematical model, equation, resonance, parameters, experimental setup, sieve, particles, amplitude, vibration frequency, productivity.

3.1 SELECTION AND JUSTIFICATION OF PHYSICAL AND MATHEMATICAL MODELS OF TECHNICAL SYSTEMS FOR MATERIALS SORTING PROCESSES

As a technical system for the processes of sorting materials, let's take a vibration screen, which is widely used in industry [1–6]. Let's imagine the sorting process as some ordered process of movement of a large number of different parts in a layer on a sieve (**Fig. 3.1**). Each share with size d characterizes its size, which does not change during movement, and is a value that can have a discrete set of values: $d_1, d_2, \ldots, d_n$. Since the number of particles in the layer is large, then d can be assigned arbitrary values in the interval of a given layer of fractions, and thus its value can be considered continuous.

H_{sup}, h_{sub} – the height of the superlattice and sublattice product; S – sieve area; Δl – sieve section; D, d – average diameter of superlattice and sublattice products; Δ – thickness of the sieve wires; V_{sup}, V_{sub} – volume of the superlattice and sublattice product.

Based on this assumption, the particle system can be replaced with a continuous model, and the productivity P will be determined by the formula:

$$P = V/t = bhv = bhl/t = sh/t, \quad (3.1)$$

where V – volume of the material layer on the sieve, m^3; t – time of transporting the material over the sieve, s; b – sieve width, m; v – sieve length, m; S – sieve area, m^2; h – average layer height on a sieve, m; v – transport speed, m/s.

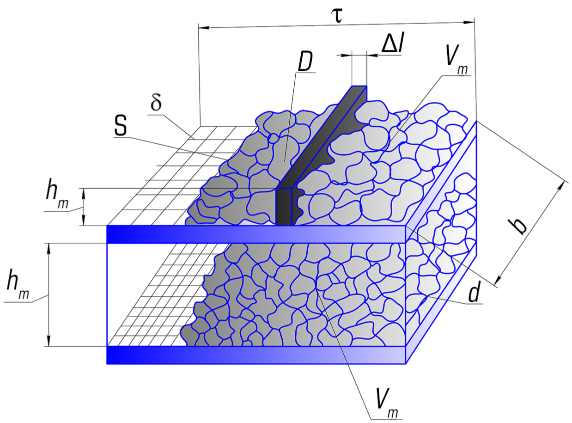

Fig. 3.1 Layout of material on the screen: l, b – length and width of the sieve

The volume can be represented as the sum of the volumes of the superlattice and sublattice materials:

$$V = V_{sup} + V_{sub} = S_{sup}h_{sup} + S_{sub}h_{sub}. \quad (3.2)$$

If to divide the sieve along its length at the level of the section Δl (**Fig. 3.1**), then:

$$\Delta l = l/n = \text{const}, \quad (3.3)$$

where n – an arbitrary number. Then the volume V_p will be distributed in equal portions V_c by Δl:

$$V_c = \Delta l_c h_{sup} b_{sup} = \text{const}, \quad (3.4)$$

where c – the number of the segment Δl.

Using the main provisions of the theory of probability [3], the process of separation into fractions can be represented as the probability p of the passage of grains d through cells D:

$$p_i = (D - d_i)^2 / (D + \delta)^2, \tag{3.5}$$

where $i=1,2,3...m$ – the serial number of the fraction, counted according to the characteristic of the size of the undersize product in the direction of growth d; d_i – the average grain size of the i-th fraction, corresponding to the characteristics of the size of half of its output; Δ – sieve wire thickness. The volume V_n distributed in this way along the length l forms a layer with the dimensions of a parallelepiped, averaging the inhomogeneity of its constituent grains. For a product with a volume of V_n, this means that all the sieve cells through which it is obtained, for the case of close alignment, a rectangle is formed, the area of which is S_n.

According to (3.4):

$$V_n = \Delta l \sum_{k=1}^{n} h_k b_k, \tag{3.6}$$

where h_k and b_k is the average value of the height and width of the layers V_k, depending on the probability p.

Consequently, the grain composition of each portion volume differs from the grain composition of similar portions of the undersize product and is a value:

$$V_k = \sum_{i=1}^{m} V_{i,k}, \tag{3.7}$$

where $V_{i,k}$ – part of the volume of the i-th fraction V_i sorted at the section Δl_k.

Under condition (3.4), the height of the i-th layer:

$$h_{i,k} = d_i p_{\min,k} / p_{bc}, \tag{3.8}$$

where $p_{\min,k}$ – probability of sieving the largest grains belonging to the composition V_c.

Considering that there is a probability that parts of the material do not pass the parts of the material $l_{i(sup)}$ ($l-l_i=l_{i(sup)}$) and condition that $1/p_{\min,k}=l_k/\Delta l$, it is possible to obtain an expression for the volume of material passage, which will be proportional to:

$$V_{i,k} = V_k \left(V_i - \sum_{i=1}^{k} V_{i,k-1} \right) \Bigg/ \left(\sum_{i=1}^{k} \left(V_i - V_{i,k-1} \right) \right). \tag{3.9}$$

Expression (3.9) is dependence for determining the rational load of the sieve during sorting based on a continuous model obtained on the probability of sorting grains.

For practical calculations, the considered model can be replaced by an adequate discrete model. For this purpose, let's express S_i, taking into account S_{sup}, through the area occupied by the fraction of grains, which are located near D in size. Let's call this fraction «heavy», that is, boundary in the general fractional composition. Then there are the following relations:

$$\begin{aligned} &S_{sup} = S_2 \Delta h_{sup} \Delta C_{sup}, \\ &S_1 = S_2 \Delta h_1 \Delta C_1, \\ &\ldots\ldots\ldots\ldots\ldots\ldots, \\ &S_{sub} = S_2 \Delta h_{sub} \Delta C_{sub}, \end{aligned} \tag{3.10}$$

where Δh – ratio of heights h_B/h_{sub}; ΔC – ratio of C_{sup}/C_h in percentage of the initial product (C_h is the yield of «heavy» grains).

From the relation (3.10) it is possible to determine the area of «heavy» grains:

$$S_2 = \left(S_{sup} + S_{sub}\right) / \left(C_1 \Delta h_B + C_{sub} \Delta h_n + C_B\right). \tag{3.11}$$

Using the probability of passing (3.5) and assuming that with each throw V_t of the layer V_h onto the sieve, «heavy» grains are sown along its width $n = b_s / d_{bc}$ and along the length of the sieve $n = 1/d_{bc}$, let's obtain the volume of limiting grains sorted in one throw of the layer on the sieve:

$$V_h = \left(\pi d_{bc} b_h \cdot l\right) / 6. \tag{3.12}$$

Then the capacity for sorting heavy grains will be:

$$P_h = V_h / T = 0.08 d_{bc} C_h l \omega. \tag{3.13}$$

Accordingly, the overall optimal power performance:

$$P = 100 P_h / C_h. \tag{3.14}$$

Taking into account (3.11), let's finally get the formula for determining the performance:

$$P = \left(S_o d \omega \left[1 - d / D\right]^2\right) / \left[\left(C_{\min} \Delta h_{Tin} + C_{av} \Delta h_{av} + C_h\right) \cdot \left(1 - \lambda\right)\right], \tag{3.15}$$

where S_o – area of the open section of the sieve; λ – voidness of the material; $\Delta h_{Tin} = h_{heavy} / h_{\min}$; $\Delta h_{av} = h_h / h_{av}$.

3.2 INVESTIGATION OF THE DYNAMICS OF THE RESONANT SCREEN, ANALYSIS AND ASSESSMENT OF ITS PARAMETERS

The proposed model [6] allows to indicate the speed of transport in the case when the sieve shaker carries out a circulating movement, which is the application of two independent vibrations with different amplitudes and frequencies. The design scheme for determining the rational parameters of screens (**Fig. 3.2**) displays a single particle on the surface of the sieve, which vibrates according to the most general laws [7, 8].

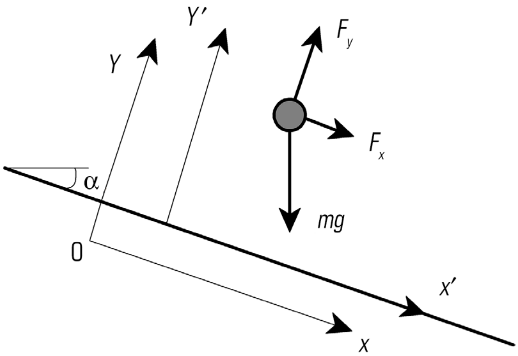

Fig. 3.2 Calculation diagram of the process of particle motion over the sieve

Differential equations for the relative motion of a particle over the sieve surface in a movable coordinate system associated with it:

$$\dot{V}_{y'} = -g\cos\alpha + X_y\omega_y^2\sin(\omega_y t + \varphi_C), \tag{3.16}$$

$$\dot{y}' = V_{y'}, \tag{3.17}$$

$$\dot{V}_{x'} = g\sin\alpha + X_x\omega_x^2\cos(\omega_x t + \varphi_x), \tag{3.18}$$

$$\dot{x}' = V_{x'}, \tag{3.19}$$

where $V_{x'}$ and $V_{y'}$ – projections of the visualization speed of the relative motion of the particle, and the last terms in (3.16) and (3.17) correspond to the inertial force of the translational motion:

$$F_x = m\omega_x^2 X_x\sin(\omega_x t + \varphi_x), \tag{3.20}$$

$$F_y = m\omega_y^2 X_y\sin(\omega_y t + \varphi_y). \tag{3.21}$$

Equations (3.16) and (3.18) do not take into account the forces of air resistance to the motion of the particle. A particle lying on the sieve surface passes into the station field predetermined by the field (3.16)–(3.19), provided that:

$$X_y\omega_y^2\sin(\omega_y t + \varphi_y) > g\cos\alpha. \tag{3.22}$$

Upon reaching the surface of the sieve in free flight ($y' = 0$), the particle strikes the surface of the sieve. The change in speed from impact can be described by the ratios of inelastic impact.

$$V_{y'}^{+} = -RV_{y'}^{-}, \tag{3.23}$$

$$V_{x'}^{+} = v_{x'}^{-} - f(R+1)V_{y'}^{-}, \tag{3.24}$$

where R – coefficient of speed recovery from the impact, f – coefficient of friction of the particle with the sieve surface, the subscripts «–» and «+» correspond to the states immediately before and after the impact. On the one hand, there is a significant uncertainty in the experimental determination of these coefficients, and on the other hand, in real conditions the particle strikes not against the sieve surface, but against the layer of particles on it, after which its relative speed is practically zero. Therefore, with an accuracy acceptable for practical calculations, it can be considered $V_{y'}^{+} = V_{x'}^{+} = 0$ with each impact. The coefficient of friction f will be defined as the coefficient of internal friction or the angle of natural slope of the bulk material. After a particle hits the surface of a sieve with layers of particles on it, several options for its further behavior are possible:

– if $X_y\omega_y^2 \sin(\omega_y t + \varphi_y) > g\cos\alpha$, then the particle is detached from the surface and continues to move above the surface in accordance with equations (3.16)–(3.19);

– if at the moment of attachment of the particle to the surface and for some next period of time $X_y\omega_y^2 \sin(\omega_y t + \varphi_y) < g\cos\alpha$, then the particle remains on the surface until the sign of the roughness changes. Its movement along the surface of the sieve during this period of time is determined by the following conditions:

if

$$\left|\left(g\cos\alpha - X_y\omega_y^2 \sin(\omega_y t + \varphi_y)\right)\right| f > \left|g\sin\alpha + X_x\omega_x^2 \sin(\omega_x t + \varphi_x)\right|, \tag{3.25}$$

then

$$V_{x'} = 0, \tag{3.26}$$

and the particle is stationary on the surface of the sieve;

if

$$\left|\left(g\cos\alpha - X_y\omega_y^2 \sin(\omega_y t + \varphi_y)\right)\right| f < \left|g\sin\alpha + X_x\omega_x^2 \sin(\omega_x t + \varphi_x)\right|, \tag{3.27}$$

then

$$\dot{V}_{x'} = g\sin\alpha + X_x{\omega_x}^2 \sin(\omega_x t + \varphi_x) - f\left(g\cos\alpha - X_y{\omega_y}^2 \sin(\omega_y t + \varphi_y)\right), \tag{3.28}$$

$$\dot{x}' = V_{x'}. \tag{3.29}$$

Consequently, the particle moves along the surface under the action of the projection of the gravity force, the variable friction force due to the variable pressing of the particle to the surface, and the longitudinal exchange force of inertia of the translational motion. The system of equations (3.16)–(3.19) with nonlinear conditions (3.25)–(3.29) can be solved only by a numerous method.

With an independent disturbance of the vibrations of the sieve in the longitudinal and transverse directions, the movement of the particle above and along the surface is rather complicated. In some practically important cases, which are necessary for evaluating certain parameters of vibration sorting, the system of equations of motion can be significantly simplified. Experiments with the model described above allow one to determine the characteristics of the motion of a particle over a horizontal surface, performing vertical oscillations, necessary for considering periodic sorting. Of these characteristics, the vibration amplitude and frequency of contacts are important, the vibration amplitude determines the increase in the layer height due to the effect of its «swelling». The frequency of contact of particles with the surface determines the conditions for their passage through the openings of the sieve. Calculations show that, regardless of the initial phase, a steady cycle of a share is formed rather quickly. From this, the amplitude of the particle tosses over the surface and the period of contacts with it are determined.

Fig. 3.3 shows the effect of the angular frequency and the amplitude of surface vibrations on the amplitude of particle motion.

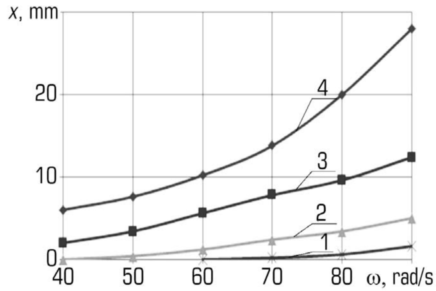

Fig. 3.3 Changing the vibration amplitude of x material particles from frequency ω: 1 – x=4 mm; 2 – x=6 mm; 3 – x=8 mm; 4 – x=10 mm

With an amplitude of 5 mm, the separation of a particle from the surface of the sieve begins at a circular frequency of 45 rad/s, and for an amplitude of 2.5 mm – generally at a frequency of 63 rad/s. The effect of circular frequency and surface amplitude on the frequency of particle-surface contacts is shown in **Fig. 3.4**.

Each amplitude has its own rotation frequency corresponding to the maximum frequency of contacts, that is, the fastest passage of particles through the holes. At a frequency of 50 rad/s, the effect of the surface amplitude on the contact frequency is not significant.

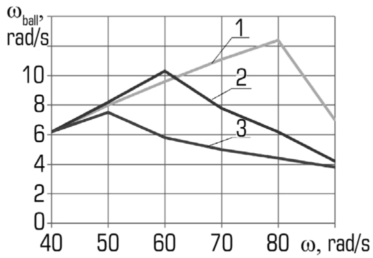

Fig. 3.4 Influence of the vibration frequency of the screen on the frequency of contacts of particles with its surface at different amplitudes: 1 – 10 mm; 2 – 2–8 mm; 3 – 3–6 mm

The sorting process is influenced by the likelihood of the passage of the grains through the openings of the sieve. This probability depends on the size of the particles, the dynamic parameters of the vibrations of the screen, the design of the screen, and the shape of the holes in the screen. The average speed of passage of particles through the sieve is determined by the frequency of contacts of the particles with the surface and the ratio of the sizes of the particle and the hole. The frequency of particle-sieve contact is influenced by the amplitude and frequency of vibrations of the screen surface. An estimate of the probability of a particle passing through the sieve opening in one collision can be carried out on the basis of the design scheme shown in (**Fig. 3.5**).

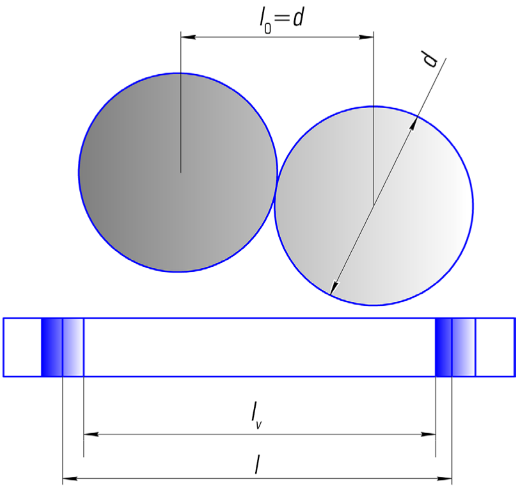

Fig. 3.5 Scheme of passage of particles through the sieve openings

Taking into account the direction of impact of particles on the surface perpendicular to it, it can be assumed that only particles which centers are inside the square $(l_0 - d)\times(l_0 - d)$ will pass into the hole. In general, particles can reach the surface anywhere in the $l\times l$ square. The probability of particles passing through the holes is determined by the relationship:

$$p = n\Delta t K_g \left(1 - d/l_0\right)^2, \qquad (3.30)$$

where $n = n(X_0, \omega)$ – the number of contacts of the particle with the sieve surface per time unit; φ – coefficient of the open section of the sieve; d – particle diameter; l_0 – hole size; Δt – time of one transition in the matrix of transition probabilities g of the cellular model of the periodic sieving process.

The angle of inclination of the sieving surface α determines the probability of particles penetrating through its holes p_f, which is determined by the angle at which the particles attack the sieve surface. This angle depends on the parameters of the vibrations of the sieve, the trajectory of the screening surface and the angle of its inclination to the horizon; it can vary within wide limits.

For experimental research, a model of a vibration screen has been developed and manufactured (**Fig. 3.6**) [9–12].

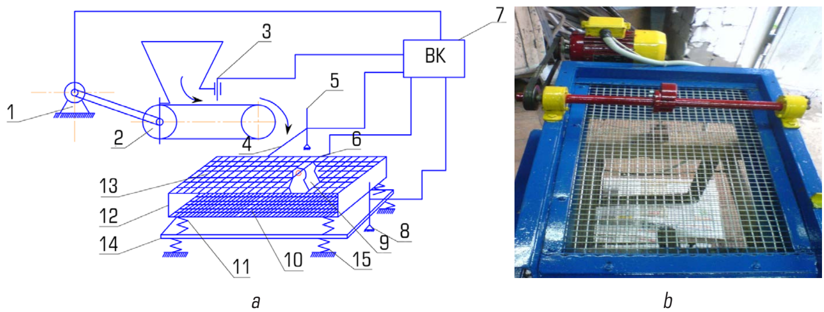

Fig. 3.6 Experimental device: *a* – diagram; *b* – general view; 1 – engine; 2 – feeder; 3 – mechanism for regulating the supply of material; 4–6, 8 – sensors; 7 – measuring complex; 9 – oscillator; 10, 13 – sieves; 12 – box; 14 – reactive mass; 11, 15 – elastic elements

The model, in terms of its design and technological parameters, is analogous to a serial vibration screen, and the ratio of the length to width of the screen was taken according to the standard ratios of 2:1.

In the course of the experiments, the search for the most efficient sorting modes was carried out.

With a certain number of throws $n_{k\max}$ and sizes of boundary grains, experimental 1 and calculated 2 graphs were built (**Fig. 3.7**).

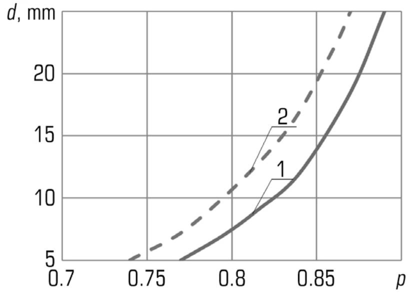

Fig. 3.7 Dependence of the probability of screening grains (the number of throws) on their size: 1 – calculated; 2 – experimental

The position of curve 2 corresponds to the position of curve 1 in terms of the proportionality coefficient $K_p = 0.95$. The probability of sorting the boundary grains of the crushed mixture according to the formula (3.5) is determined by the ratio:

$$P_{sor} = \frac{\left(l - K_n d_{bc}\right)^2 K_g}{\left(l + d\right)^2}. \tag{3.18}$$

In accordance with this correction, let's perform calculations of the optimal productivity and the corresponding screening efficiency for experimental screening units. At the same time, let's neglect a similar correction for light grains, taking into account the insignificant size *dl*.

Let's find the average value of the grain size composition of the material in each experiment and the empirical dispersion S^2 for each fraction. As an estimate of variances, let's take the weighted average number of individual empirical variances.

Let's compare the obtained permissible measurement accuracy, having previously determined the nature of the variance discrepancies by the ratio.

The critical value of these ratios for the degrees of freedom $K_1 = 49$ and $K_2 = 13$, $F \approx 2.3$. This confirms the random nature of the variance discrepancies and the absence of a significant difference in the measurement accuracy in individual experiments. Hence, with a reliability $P = 0.95$ and an accuracy S' for the actual grain size composition of the material, one can take the average, compiled according to the data of all experiments. As the result shows, the initial characteristic of the size of the material practically did not change during the experiments. Using the experimental and calculated points, let's build the graphs of the dependence (**Fig. 3.8**).

Analysis of experimental data on the number of throws $n_{k\max}$ revealed the following. The value $n_{k\max}$ is influenced by two main parameters: the time of transporting the material over the sieve t and the frequency of forced vibrations of the vibrator. The time of transporting the material t increases the screening efficiency E even in the case when the limiting grain size d_{bc} is large, i.e. $d_{bc}/D > 0.9$. On the other hand, an increase in the parameter t reduces its vibration transport speed v, which reduces the total amount of material passing through the screen per unit time. For example, at t=5 s, P=26...43 kg/min; for t=6 s, P=21...38 kg/min; for t=7 s, P=16...24 kg/min; for t=12 s, P=9...21 kg/min; for t=16 s, P=3...14 kg/min; for t=26 s, P=4...9 kg/min. The graphical meaning is shown in **Fig. 3.9**.

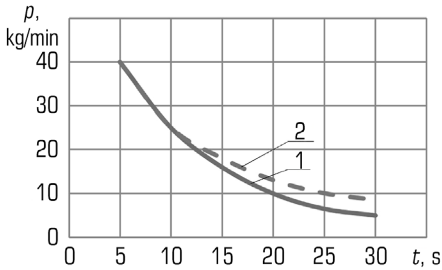

Fig. 3.8 Dependence of rational sorting productivity on the time of material transportation over the sieve: 1 – calculated; 2 – experimental

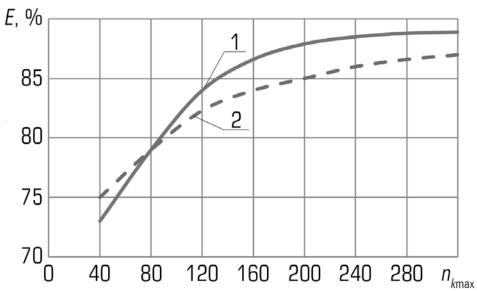

Fig. 3.9 Dependence of the maximum sorting efficiency on the number of throws of the material layer on the sieve: 1 – calculated curve; 2 – experimental curve

As can be seen from the above examples, with an increase in the residence time of the material on the sieve t_m, an inversely proportional decrease in the productivity of the vibration screen is observed. The size of the sorted material has a significant effect on the value of productivity. In this case, the productivity P can vary up to 42 %. For example, in the case of transportation during the time of material t=12 s at d_{bc}=8.4 mm, at $d_{bc}/D = 0.907$ and S_h=9.64 %, the productivity of the screen P=10.2 kg/min, and at d_b=8.32 at $d_{bc}/D = 0.924$ and S_h=10.8 % screening capacity is 12 kg/min.

Analysis of the experimental data (**Fig. 3.9**) on the number of material throws $n_{k\max}$ over the sorted material and their influence on the main technological parameters showed that the discrepancy is 5.3–8.1 %.

3.3 DISCUSSION OF RESEARCH RESULTS

The studies carried out revealed the influence of the vibration frequency and the angle of inclination on the efficiency of sorting. So, with an increase in the frequency of vibration and the amplitude of vibration of the box, the separation of the material and the speed of sorting increase. The particle speed is of greater importance at the frequency of the box vibrations, $\omega = 45...85$ rad/s. When changing the angle of inclination from $\alpha = 2°...204°$ it was obtained that with an increase in the angle of inclination of the sieve from 14° to 20°, the concentration, speed and power are more stable. The dependence of the used power on the design and technological parameters of the vibration screen is revealed. The number of throws to be sorted is influenced by the transport time *t* of this material over the surface of the sieve and the amount of vibration excitation to this material. These parameters are due to the magnitude of the forced vibrations of the vibration system, with an increase in both of these parameters [13–16].

An increase in the number of throws of material $n_{k\max}$ increases the residence time of the material on the surface of the sieve, reduces the speed of passage of the material and, in general, reduces the productivity of the screen. For example, for $n_{k\max} = 49$, $P = 26...43$ kg/min with an increase $n_{k\max}$ to 67, the productivity of the screen *P* decreases to 16...24 kg/min, for $n_{k\max} = 211$ it decreases to 3...14 kg/min, and with a value of $n_{k\max} = 367$, the productivity of the screen is only about 8.1 kg/min.

The efficiency of the sorting process *E* is also affected by $n_{k\max}$ as follows: with the number of throws $n_{k\max}$ indicated in the previous paragraph, the efficiency of screening *E* is respectively: 87.9 %, 89 %, 91.5 %, 94.7 % (**Fig. 3.9**, curve 2). The increase in the efficiency of screening *E* in accordance with the increase $n_{k\max}$ is explained by the increase in the time of vibration exposure to the medium being separated. This is confirmed by the close placement of curves 1 and 2 (**Fig. 3.9**).

CONCLUSIONS TO SECTION 3

1. The physical and mathematical model of the screen has been substantiated, on the basis of which the equations of material movement over the sieve are compiled.

2. Distribution of the vibration amplitude of the material particles from the vibration frequency of the sieve has been determined.

3. An experimental model of a vibration screen has been developed and experimental studies of its operation have been carried out.

4. Dependence of the used power on the design and technological parameters of the vibration screen has been revealed.

5. The influence of the vibration frequency and the angle of inclination on the sorting efficiency has been determined. So, with an increase in the frequency of vibrations and the amplitude of vibrations of the box, the separation of the material increases and the particle speed is of greater importance at a frequency of vibrations of the box of 45...85 rad/s.

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