DOI 10.31489/2020No2/100-109

UDC 622.784. 622' 17. 22.23.05

TECHNOLOGY AND EQUIPMENT FOR PROCESSING OF LARGE-SIZED VERMICULITE MICAS OF THE KOVDOR DEPOSIT

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The development of technology and equipment for the processing of large-sized vermiculite mica obtained from mining waste from the Kovdorsky deposit allows the large-scale vermiculite to be returned to processing industry. This article reviews the aspects of the technology for processing of large-sized mica with dimensions of 20 mm or more. The aim of the research is to study the grinding technology of large-sized vermiculite raw materials by the chopping overall particles, to develop the technological equipment and to study of its operating processes. The object of the research is the operating process of the chopping unit for grinding the large-sized vermiculite raw materials and its design. The methods are based on study of simulated movement of chopped large-sized particles and the determination of the main characteristics of the chipping unit operating process. It was found that the firing of large particles without grinding in chopping units requires a significant increase in firing time, which reduces the productivity of electric furnaces. The time of dropping particles out in the slot of the receiving drums of the chopping unit is determined, based on which the rotation speed of the receiving drums and its operational efficiency are calculated.

Keywords: large-sized vermiculite mica, chopping unit, expanded vermiculite, industrial furnace.

Introduction

The expanded vermiculite has a rare property to enlarge in size when heated and change the original structure from flat mica particles to bulk grains of slit-like structure, while reducing its density by 8...12 times. This property has provided vermiculite with wide application in various areas: production, construction, environmental and other human activities. Vermiculite is under studying still now. The technologies using different fractions of this unique material are developing. The new equipment for the implementation of these technologies [1-15] is being designed as well.

A large-scale study and application of expanded vermiculite began in the second half of the twentieth century in our country, and the industrial development of the world's largest Kovdor phlogopite-vermiculite deposit in the Murmansk region began in 1965 with the development of the main phlogopite deposit located under the vermiculite deposit. To get to phlogopite, a raw material that was more in demand at that time, it was necessary to exhaust vermiculite ores and create several warehouses with different vermiculite contents and a warehouse of vermiculite-sungulite rock.

The processing of vermiculite ores began in 1975, but the processing plant operated only on rich stored and recovered ores. The enrichment technology was based on the use of gravity methods and according to the cadaster of mining waste [16], the extraction of vermiculite was at a low level, which characterizes the very high quality of the tailings sent to the tailing dump.

The material with grain size larger than 20 mm, without being in demand, was discharged into the dry tailings dump without any enrichment. Among the present technologies and equipment, the hammer crushers with cutting blade hammer have got good application perspectives. At the same time, there is a high level of wear of the operating tools. Grinding by other machines (jaw, cone, roller and others) reduces the crushing quality of vermiculite particles. They flake, partially crumble, but doesn't change in overall dimensions significantly. Application of the proposed equipment will not have the mentioned above disadvantages

The issues of improving the technology of processing vermiculite-sungulite conglomerates were reviewed in the article [16]. In a number of other publications, for example [17-20], the issues of returning depleted vermiculite ore and tailings stocks to industrial circulation were considered. This article reviews some aspects of technology and equipment for processing large-sized mica grain ore with dimensions of 20 mm and larger, located in the dumps of dry tailings for the production of expanded vermiculite.

1. Samples and Research Methods

Large-sized row vermiculite mica grains with a vermiculite content of 15...20% by weight [16] is extracted from storage facilities and subjected to gravitational enrichment according to the technology developed at Kovdorslyuda OJSC using slot separators and brought to a target product concentration of 90...95%. Then the resulting material was sent chopping units for grinding to a given size in.

The optimal particle size of vermiculite concentrates depends on the purpose of the expanded product, which is determined by the consumer, but not only by him. JSC "Kovdorslyuda" produced concentrates of size groups KVC-8 and KVC-16, but they were used only in hydroponics, and mainly outside the country, and their firing was a very costly process, since it was carried out in fired furnaces operating on hydrocarbon fuel. Without going into energy calculations, let's try to determine roughly the optimal firing time and the corresponding maximum particle size of the concentrate.

The article [19] describes the research during which the dependence of the calculated time of firing in electric furnaces of concentrates of vermiculite particles of various size groups was set up on the basis of analytical modeling of the layered thermal conductivity of the plates of expanded vermiculite. Vermiculite ore concentrates have a very inhomogeneous particle size, but the distribution of particle sizes approximately obeys the normal distribution of random variables [19]. If a concentrate in a volume of 1 m^3 contains particles with nominal diameters from 1 to 7 mm and more (Figure 1), then the time of their firing to complete expanding will correlate with their sizes.

Fig.1. Photo of granulometric heterogeneity of concentrate KVK-4 of the Kovdorskoe field.

The larger the particle, the more time it will take, and the ratio $t_{\text{omax}}/t_{\text{omin}}$ can reach twelve. Therefore, vermiculite should be fired only after preliminary separation into fractions in order to spend less energy, without overfiring the small particles and not leaving the largest ones unexpanded. This is an accompanying question, but it is closely related to the tasks being solved here.

The study of layered thermal conductivity, based on the principle of equalization of temperatures from the periphery to the center of the plates of expanded vermiculite grains, led to a simple analytical dependence for determining the sufficient duration of firing [19]:

$$t_{\text{f}} = 0.4\frac{d_{\text{c}}^2}{a}, \tag{1}$$

where *a i*s the coefficient of thermal conductivity, m^2/s (a=2.9·10 $^{-6}$ m^2/s [19]); d_{c} is conditional particle diameter, determined by the formula:

$$d_{\text{c}} = \sqrt{x^2 + y^2},$$

where *x* and *y* are the maximum and minimum particle sizes.

According to the formula (1), the values of the time of complete expanding of the vermiculite concentrate particles during firing and the corresponding particle sizes were calculated (Table 1).

Into the analytical dependence (1) does not include the surface temperature of the expended vermiculite grain at the end of the firing process, but the given formula was obtained for a value of 599 ºC, which was roughly determined as optimal for electric furnaces with a heating element temperature of 720...750 ºC. The indicated temperatures were measured during the experimental research of a pilot industrial modular-firing furnace in 2015. Using a pyrometer, we determined the heating temperatures of the surface of expanded

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grains at the exit from the furnace, with their full and high-quality expanding, which were in the range 586...612 ºC (with an average value of 599 ºC) [19].

Table 1 - Nominal particle diameters and their firing time until full expansion

d_y, [mm]	1.0	2.0	4.0	6.0	8.0	10.0	12.0	14.0	16.0	18.0	20.0
t_o, [s]	0.068	0.27	1.09	2.44	4.34	6.79	9.78	13.31	17.38	21.99	27.15

The other increased temperature conditions with heating of radiant electric heaters over 750 ºC allow to reduce the firing time, but at the same time increase the risk of soot deposit on their surfaces and reduce the reliability of the furnaces. Figure 2 shows the dependence of the firing time on the nominal diameter of the vermiculite concentrate particles, which does not depend on the type of ore from which it is obtained (Kovdorsky, Koksharovsky or Tatarsky concentrates). From the graph analysis it follows that the firing of large-sized concentrates without preliminary grinding of particles with large sizes requires an increase in firing time, which will lead to a decrease in the productivity of electric furnace units. Therefore, Figure 2 shows a graph of the dependence of the firing time on the nominal diameter of a particle with a maximum size of 10 mm.

With the nominal diameter d_c=4 mm, corresponding to the Kovdor concentrate KBC-4, the calculated firing time is 1.086 s (Figure 2). But in the massif, as noted above, there is a large number of particles with sizes of 7...8 mm, therefore, when setting up the furnace unit, the value to is adjusted so that the largest particles are completely swollen. Consequently, the real time to during firing of KBC-4 concentrate should be 3.39 s (Figure 2). The experimental value of the duration of heat treatment in a furnace with a movable base platform [17] during firing KVC-4, at which the highest productivity is achieved, is approximately 3.1 s - point *a* (Figure 2).

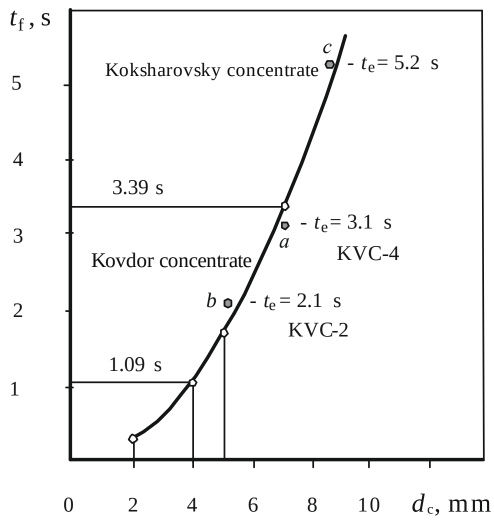

Fig. 2. The dependence of the firing time on the nominal particles diameter of vermiculite concentrate.

For KVC-2 concentrate with d_c=2 mm, the firing time is 0.27 s (Table 1), but the actual calculated t_o, taking into account large particles up to 5 mm, should be 1.78 s. In the experiment, it was equal to about 2.1 s – point *b* (Figure 2). The third experimental point *c* was added during experiments with the Koksharovsky concentrate KBC-4. The size of the maximum particles reached 8.5...9 mm in it. The firing time was 5.2 s (Figure 2). We have already noted above that heat treatment of concentrates without preliminary grinding of large-sized particles is not profitable due to a decrease in productivity and an increase in energy consumption. Therefore, we will proceed to consider the technology and equipment for their preparation and grinding.

2. Technology and equipment for grinding large-sized micas

Concentrates of the Kovdorskoye deposit, the KBC-8 and KBC-16 grades, before they are fired in electric furnaces, must undergo preliminary fractionation, for example, on a drum sieve, at the outlet of which all particles with sizes exceeding 10 mm are collected in a separate bin. This is the preliminary preparation of raw materials. All other particles that pass through the sieve go to the firing. Large-sized particles of more than 20 mm after gravitational enrichment according to the proven technology using slotted separators, extracted from the dumps, are sent for grinding in chopping units.

Figure 3 shows the of the chopping unit device. It contains a hopper 1, a dispenser 2 with a feed drum 3 and a flow divider of large-sized mica particles 4, made in the form of alternating crossed plates. The dispenser drum is connected to an adjustable gear motor (not shown in Figure 3) and a chain drive with one of the receiving drums, for example, 5, the shaft of which is connected to another receiving drum 6 by a gear drive, which provides their rotation with equal angular velocities ω in opposite directions. The trays 7, leading from the flow divider 4 to the receiving drums, reinforced with stiffening ribs 8, have projections 9 in the lower part and channels 10 (Figure, 4 *a*), inside them. There are longitudinal slots 11 in the drums 5 and 6, and the channels 10 in the projections 9 are parallel to them.

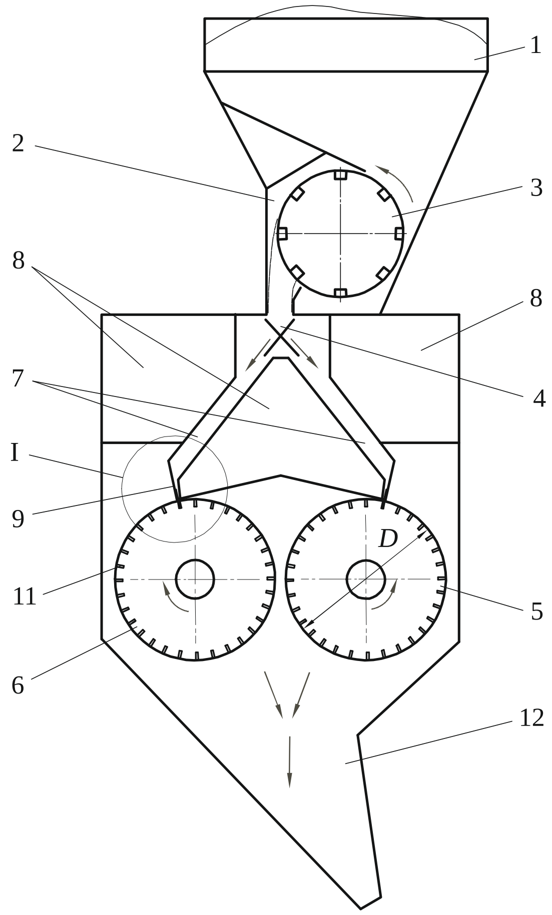

Fig.3. The schematic diagram of the chopping unit.

The drum dispenser delivers the large-sized concentrate to the flow divider, which distributes approximately equally the mica particles along the trays 7. The slots 11 in the receiving drums have a depth of h=10 mm. When large particles of mica come from the flow divider and go down the trays 7, they, being in the channels 10, abut against the surfaces of the rotating drums 5 and 6, and slide along them until they fall out into the nearest slot 11 (Figure 4, *a*).

The receiving drums, turning with a certain angular velocity ω, chop off the particles on the projections 9 of the trays 7 and carry them until they fall out under their own weight into the lower part 12 of the hopper of the chopping unit body. The remainder of the chopped off particle, sliding along the surface of the receiving drum, falls into the next slot and this happens several times on each drum 5 and 6 until all particles are chopped into narrow strips 10 mm wide and length determined by its original size, for example 20...30 or 20...40 mm (Figure 5). Feeding of large particles of mica by the dispenser drum is selected so as to exclude more than two particles from falling into one place in the slot 11 in order to avoid their jamming. The width of these slots is such that two particles can be located in it without jamming. In this case, two particles are chopped off at once. This process of gradual splitting of particles into strips occurs across the entire width of

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each of the receiving drums. Stiffening ribs 8, located at an equal pitch one after the other, exclude sagging of the projections 9 during the particles chopping off.

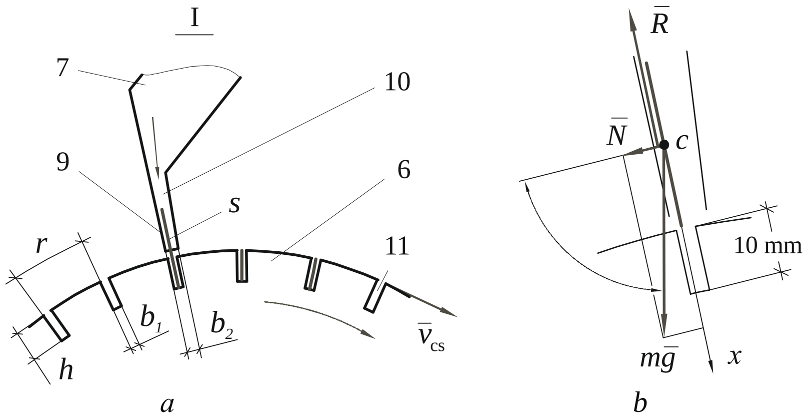

Fig.4. Schemes: *a* – design diagram of the technical characteristics of the unit (fragment I according to Figure 3); *b* – scheme of forces acting on a particle.

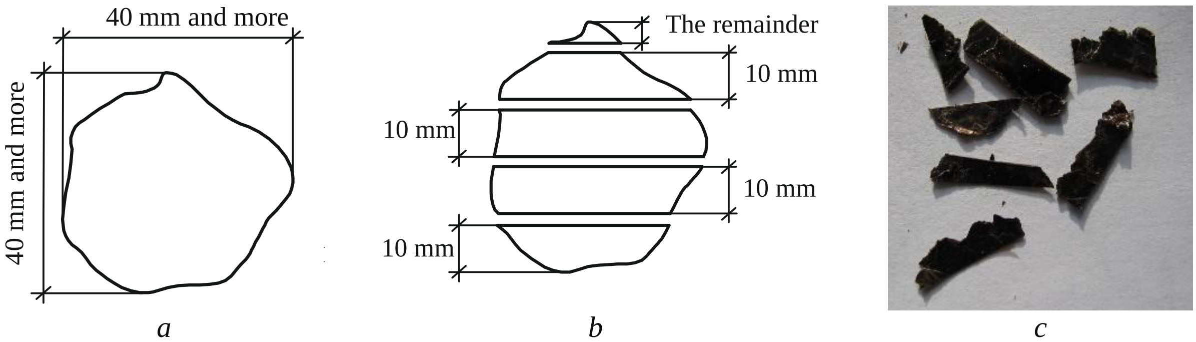

Fig. 5. The shape and size of the particles of large-sized concentrate: *a* – original; *b* – after cutting into strips; *c* – photograph of a chopped particle

The chopping unit provides a gradual reduction of only one particle size to 10 mm, while its other size remains unchanged and equal to 20 mm or more, depending on its initial size (Figure 4). But in order for the chopped particles to expand quickly at a temperature of the heating elements of the furnace of 720...750 ° C, this is enough [19], since the radiant energy, according to the model of the layered thermal diffusivity of vermiculite plates, penetrates from both sides in the transverse direction over a size of 10 mm (by 5 mm left and right).

3. Chopper unit work process theory

Based on the principle of the chopper unit operation, let's determine its technical characteristics, having the following initial data:

- outer diameter of receiving drums 5, 6 (Figure 3) – D=1 m;
- the width of the receiving drums 5,6 (Figure 3) – B=1.25 m;
- the depth of the transverse grooves (Figure 4, *a*) – h=0.01 m;
- width of transverse grooves (Figure 4, *a*) – b_1 = 0.0025 m;
- the width of the channels in the projections of the trays (Figure 4, *a*) – b_2=0.003 m;
- angle of inclination of trays projections to the vertical – 16 °.

The angular speed of rotation ω of the receiving drums can be calculated by considering the dynamics of the process of a mica particle motion at the moment of its falling out of the channel 10 into the transverse groove 11 of the drum 6.

Let's consider the design scheme (Figure, *b*). The *x* axis is directed downward along the surface of the mica plate. The point *c* is the center of gravity of a plate of mass *m*, so its motion when falling out can be described as the motion of a material point *c*.

The differential equation of its motion will be:

$$m\ddot{x} = mg \cdot \sin\alpha - mgf \cdot \cos\alpha, \quad (2)$$

where *f* – is the coefficient of sliding friction of vermiculite mica on steel (for large-sized Kovdor concentrates *f* ~ 0.68 [20]).

Reducing equation (2) by the particle mass, dividing the variables and integrating twice over the time of motion τ, we get:

$$x = 0.5\ \ g \cdot \sin\alpha - fg \cdot \cos\alpha\ \ \tau^2 + x_0. \quad (3)$$

Since the initial velocity of falls out particle is equal to zero, and in equation (3) the initial coordinate x_0 is zero, then solving the quadratic equation (3) with regard to τ, we obtain the time of motion of the mica plate when falling into the slot of the receiving drum:

$$\tau = \sqrt{\frac{2x}{g \cdot \sin\alpha - fg \cdot \cos\alpha}}. \quad (4)$$

Since the depth of the grooves is *h*=0.01 m, then the drop-out path is *x* = 0.01 m, and the angle α is equal to: 90° – 16° = 74°.

Substituting the indicated values and the coefficient of friction into expression (4), we obtain the dropout time or slot filling time:

τ = 0.052 s.

For further modeling of the operating process of the chopping unit, determining the circumferential speed of its receiving drums, and then the angular speed of their rotation, let's make a number of assumptions:

- all mica particles have a thickness of *s* = 0.001 m;
- all particles have a rectangular shape with a width of *e*=0.02 m and a surface area equal to the areas of real particles averaged over the conventional diameters d_c;
- in a time τ = 0.052 s, the receiving drum rotates through an angle corresponding to the arc of its circumference, equal to half the width of the groove – 0.5 b_1;
- the particles in the grooves of the drums are arranged in one row tightly to each other.

Let's determine the circumferential v_{cs} and angular ω speed of the receiving drums:

$$v_{cs} = \frac{0.5 \cdot b_1}{\tau} = \frac{0.5 \cdot 0.0025}{0.052} = 0.0241 \text{ m/s}; \quad (5)$$

$$\omega = \frac{v_{cs}}{0.5D} = \frac{0.0241}{0.5 \cdot 0.1} = 0.0482 \text{ rad/s}. \quad (6)$$

Let's determine the speed:

$$n = \frac{30\omega}{\pi} = 0,46 \text{ rpm}. \quad (7)$$

After the particle falls out into the groove, it takes some time for it to jam between the walls of the groove and the channel of the tray, i.e., to select the gaps due to the dimensions b_1 and b_2, which corresponds to the length of the arc:

$\lambda = b_1 + b_2 - s$ = 0.0025 + 0.003 – 0.001 = 0.0045 m.

After jamming, the particle is chopped off in a time corresponding to the arc length equal to the mica particle thickness *s*. However, mica has a layered structure, which makes it difficult to shatter, therefore chopping process takes longer to completely separate the severed part from the main particle. To guarantee the results we model this process with time allowance three times longer time then actual chopping time and the length of the drum arc l_a corresponding to this time, equals to:

$l_a = 3s$.

Then the time of one cycle (from the moment the first particle falls out until the second one falls out) will correspond to the circular arc of the receiving drums corresponding to the step of the slots *r*:

$r = \lambda + s + l_a$ = 0.0045 + 0.001 + 3·0.001 = 0.0085 m.

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With a drum diameter of 1 m, the ratio of their perimeter L to step r gives the number of chopping cycles k for one drum revolution. For a two-drum chopping unit shown in Figure 3, the total number of chopping cycles will be:

$$k = \frac{2L}{r} = \frac{2\pi D}{r} = \frac{2 \cdot 3.14 \cdot 1}{0,0085} = 739 \cdot$$

Dividing the resulted value by the rotational speed n, we get the number of choppings per minute:

$$K = \frac{k}{n} = \frac{739}{0,46} = 1606 \text{ (96390 per hour).}$$

With a drum width of 1.2 m and a conventional particle width of e=0.02 m, 60 rectangular plates with dimensions of 20×10 mm are separated in one chop, and their total number falling into the lower part of the chopping hopper per hour is 5783400 pieces. If the thickness of the plate is 0.001 m, then the volume of all the plates dropped out per hour is:

$$V = 5783400 \cdot 0.001 \cdot 0.02 \cdot 0.01 = 1.157 \text{ m}^3.$$

The true density of hydromica is approximately equal to 2300 kg/m^3 [7], so the resulted volume can be converted to mass:

$$m = \rho V = 2300 \cdot 1.157 = 2661 \text{ kg}.$$

This value is equal to the theoretical hourly productivity of the chopping unit – 2.66 tons/hour.

Let us write down the formula for the theoretical mass productivity of two drum chopping units in general form (kg/h):

$$P_t = 60 \frac{2\pi BDsd_c}{r \cdot n} \rho, \tag{8}$$

where d_c is the average nominal diameter of a vermiculite mica particle from the bulk of the initial enriched large-size concentrate, m. In this case, the drum rotation frequency n should be determined with the consideration of the formulas (5-7).

If we recalculate the mass productivity for the volumetric (after firing in the furnace) according to the formula (m^3/h):

$$P_v = k_e P_t.$$

If we take into account the expanding coefficient for large-sized Kovdor concentrates KVC-8, which are closest to that obtained from chopped mica plates, equal to k_e ~ 10.8 m^3/t, we obtain an approximate value: P_v=28.7 m^3/h. Taking into account the operational factors that reduce the theoretical productivity by 12...15%, it is possible to determine the actual monthly mass productivity of one unit with the parameters given above:

$$P_t = 1630\ldots1685 \text{ tn /month.}$$

This will allow loading 27...28 railway open-top wagons with chopped vermiculite concentrate per month.

4. Unit operation as part of a specialized electric furnace

The two-drum unit with considered operational factors is capable of producing, on average, after firing in a furnace, expanded vermiculite about 24.8 m^3/hour. If we reduce the width of the receiving drum to 1 m, and the diameter to 0.9 m, then such a single-drum unit can be built into the dosing system of a three-module electric furnace with a vibrating base platform [17, 18] and process large-size concentrates immediately before firing at the consumer. Focusing on formula (8), we obtain the productivity of such a furnace for expanded vermiculite:

$$\frac{0.5 \cdot 24.8 \cdot 0.9}{1.2} = 9.3 \text{ m}^3/\text{hour},$$

which roughly corresponds to the performance of an electric furnace with two power technology units (with P_v of 4.5 m^3/h each) and vibrating platforms with forced kinematic excitation (Figure 6) [22].

An industrial furnace consists of two identical energy technology blocks and contains a frame 1, baking trays 2 with movable bases 3, thermally insulated covers 4, electric heaters 5 fixed on the fixing heads 6, rollers 7 located in guides 8 installed transversely to the flow direction of the expanding chopped vermiculite moving along the base plates. Movable bases are placed obliquely, parallel to each other and one above the other. The furnace also contains a gear motor 9, a drive shaft 10 mounted in bearings 11 with eccentrics mounted on it. The eccentrics are equipped with rolling bearings (in the figure they are covered with movable bases and are not visible), which are rotated on shaft 10 relative to each other by 120 °.

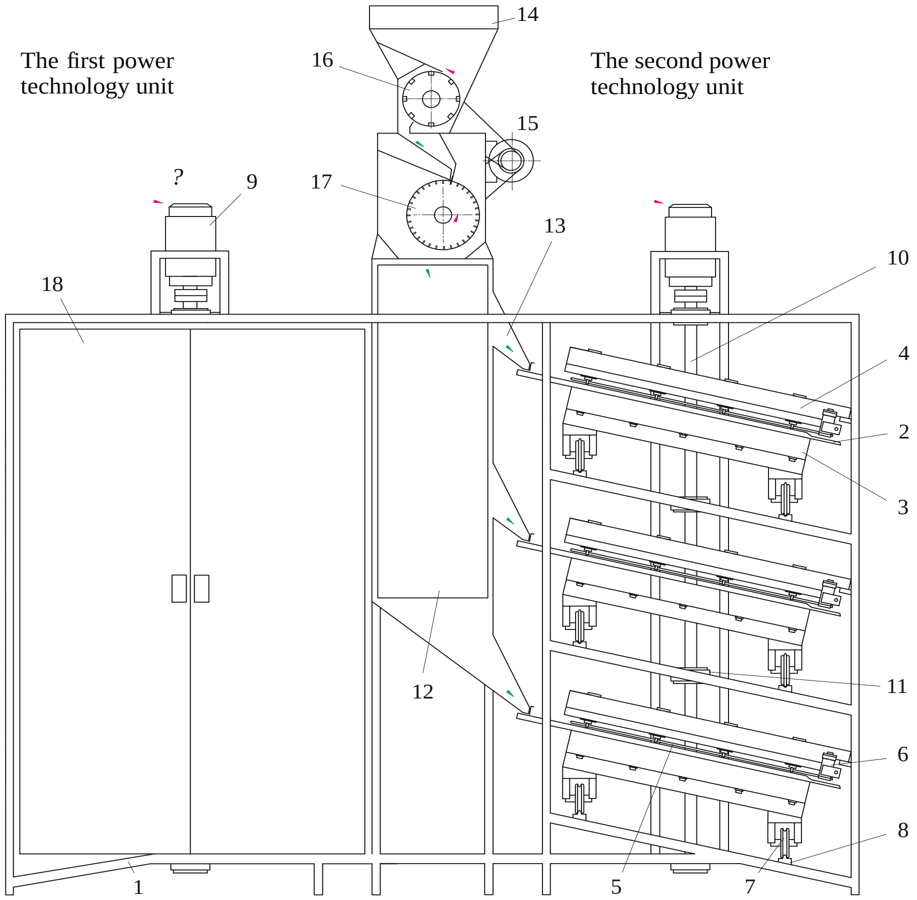

Fig. 6. Industrial furnace consisting of two technological units with a chopping unit built into the raw material dosing system

The hopper 12 for chopped vermiculite concentrate is located in the central part of the furnace and has trays 13 with slide gates installed with gaps above the parts of the base plates 2 protruding on the left. A single-drum chopping unit is installed on the hopper and in this embodiment has a drum dispenser 14 and a drive 15, which is configured so that its transmissions set the rotation of the dispenser drum 16 and the receiving drum 17 with such a ratio of angular velocities at which the excessive supply of concentrate to the chopping unit and wedging of particles in the lateral slots of the drum are eliminated. The furnace is closed on all sides by thermally insulated doors 18, which are conditionally removed on the second power technology unit.

During the operation process, the bearings of the eccentrics, when the shaft 10 rotates with an angular velocity ω, act on the protruding parts of the movable bases 3 and cause their transverse harmonic vibrations with regard to the vermiculite flow with an amplitude *A* equals to the eccentricity value, which is the same for all eccentrics of the drive shaft. In this case, the springs (not shown in the figure) installed on the sides of the movable bases 3 opposite to the eccentrics provide their return movement [23-27]. Under the action of transverse vibrations, the vermiculite concentrate from the hopper 12 through the trays 13 gradually fed onto the protruding parts of the base plates 2 and, moving along their surfaces, enters the thermal field of the electric heaters 5 under the thermally insulated covers 4 and in 3.5...4 under the action of high temperature expands and comes out of the furnace (right and left). The slide gates of the trays 13 provide control of the thickness of the layer exiting the raw material trays 13.

In the electric furnace under consideration, the vibrations of the movable bases are forced by the eccentrics of the drive shaft. Therefore the system does not operate in a resonance mode, which is very sensitive to fluctuations of various factors that affect the stationarity of vibrations and the parameters of

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vibration transportation of chopped concentrate along the base plates. For example, if there are changes in the excitation frequency ω, then the amplitude will remain equal to the eccentricity, and this will provide steady fluctuations of the bases 3 and the stationarity of the technological firing process, the duration of firing will not change, there will be no vermiculite expanding or overburning, and the furnace productivity will remain unchanged. Even the contamination of the guide runners 8 with fine vermiculite formed during expanding cannot affect the change in amplitude, since the oscillations are set by the drive shafts 10 and the gear-motors 9 forcibly.

Conclusion

On the basis of the analytical dependence, there were calculated the values of the expanding time of particles of large-sized vermiculite concentrates for the required sizes during firing in electric furnaces with a heater temperature of 720 ... 750 ° C. But these results can be considered as indicative before a study of the process on a physical model is conducted.

Analysis of the graphical dependence correlates with the experimental data and shows that firing large-sized particles without grinding them in chopping units will require a significant increase in firing time, and this will negatively affect the electric furnaces capacity with movable bases. Therefore, the optimal longitudinal size of the obtained particles of chopped vermiculite concentrate is taken to be 10 mm, which is the minimum sufficient, since the radiant energy of the heaters, according to the model of the layered thermal diffusivity of vermiculite plates, penetrates from both sides in the transverse direction, 5 mm from the left and right.

The research of the dynamics of the motion of particles when they fall out into the slot of the receiving drums has shown that the time of this falling is about 0.052 s, including friction. Based on this time and the specified parameters of the design elements of the chopping unit, the angular speed of rotation of the receiving drums and the operating capacity of the two drum unit were calculated. It is equal to 1630...1685 tons/month, which corresponds to a monthly shipment of chopped concentrate in the amount of up to 28 railway open-top wagons per month.

The indicated volumes correspond to 18000...20000 m^3 of expanded vermiculite. The basic two-drum chopping unit is designed for operation at the deposit and processing of large-size concentrates obtained by enrichment from stored and newly obtained vermiculite micas.

It is possible to use its single-drum version with reduced dimensions of the receiving drum and other design elements as a chopping mechanism built into the dosing system of industrial electric furnaces with movable base platforms in the production of expanded vermiculite at the construction industry enterprises. In this case, the consumer buys enriched vermiculite concentrate, consisting of large particles with nominal diameters of 20...40 mm. Such a chopping mechanism is capable of ensuring the operation of a double industrial electric furnace of two energy technology blocks with a capacity of approximately 9.5 m^3/h.

The proposed technical solution has good application perspectives for the processing of particles of large-scale raw materials from other deposits.

Acknowledgments

The research is carried out at Tomsk Polytechnic University within the framework of Tomsk Polytechnic University Competitiveness Enhancement Program grant.

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Article accepted for publication 21.10.2020

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