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Thermal Unit with Controlled Distribution of Flow Speeds of Processed Raw Materials in Zones of Electrified Modules

The article reviews the possibility of thermal treatment of vermiculite concentrates in thermal units of the modular-launch type after the defects of the units appeared during operation were fixed. It was observed that the temperatures of the electric heaters and the refractory surface of the firing modules distribute unevenly horizontally: the temperatures decreased significantly from center to periphery. This feature showed a technical solution — the division of the total flow of the expanded vermiculite into local and controlled flows between the thermal zones of the furnace modules taking into account their temperatures. The required time for particles movement in each thermal zone was determined, as well as average local speeds of their movement in the indicated zones were by comparing the thermal capacities of local vermiculate flows. The calculations of local flow rates were carried out and the total productivity of the modernized furnace was determined. The productivity of modernized furnace is 24% higher than the prototype furnace. It is shown that with an increase in productivity but equal to electricity consumption, the specific energy consumption of firing processes decreases by the same 24%. It makes the furnace more perfect and competitive.

Keywords: electric modular–launch furnace, firing module, non-uniform temperature distribution, temperature zones, accelerating tray, heaters, heat power, average local speeds, local productivity, total productivity.

Introduction

The research in the field of technologies for the production and use of expanded vermiculite has been conducted since the 30s years of the last century. This indicates the relevance of this issue and the importance of the product [1–11]. Electric furnaces for vermiculite firing, which will be reviewed in the article [12], were developed in the early 2000s as an alternative to fired furnaces operating on hydrocarbon fuel [9].

The expanded particles' streams in such furnace units have been uncontrollable till the present time and their flow was determined by the action of the gravity forces of the particles. This is their obvious disadvantage.

Even in the very first modular-launch furnaces (2003–2005), it was noticed and experimentally confirmed that the temperatures of suspended heating elements and refractory surfaces of firing modules were distributed non-uniformly.

Temperature measurements in different areas showed that in the central zones of the modules, the temperatures of the refractory bases are significantly higher than in the side zones. During the heat treatment of vermiculite at the furnace exit in the central zone, the end product was completely expanded, but overheated and partially burnt, and in the edge zones it remained under-expanded. This feature illustrated a technical solution – to separate the flow of expanded vermiculite into local flows in thermal zones, taking into account their temperatures, and to develop a system for controlling local flows.

The purpose of the research is to increase the efficiency of the thermal unit by means of the rational distribution of local flows of heat-treated raw materials along the width of the firing modules without the increasing of its electrical power.

Experimental

Consideration of the furnace design and operation.

Vermiculite concentrate is supplied to the furnace by a dispenser equipped with a hopper 1, a drive 2, a drum 3, and an inclined tray 4 by length l_0. The raw material through the inclined tray 4 is poured onto the accelerating tray 5 of the upper module 6. Then the raw material goes to the firing space under the cover 7, where the electric heater 8 is fixed. It is held by the hooks 9 and the fixing heads 10 (Figure 1). Then vermiculite is poured onto the second accelerating tray 11 of the middle module 12 and then onto the tray 13 of the lower module 14. The finished product comes out from the tray 13 of the lower module 14. The firing space 15 of each module is formed by a refractory surface 16 made of refractory bricks, by the lower part of the cover 7 and by side walls (not shown in Figure 1).

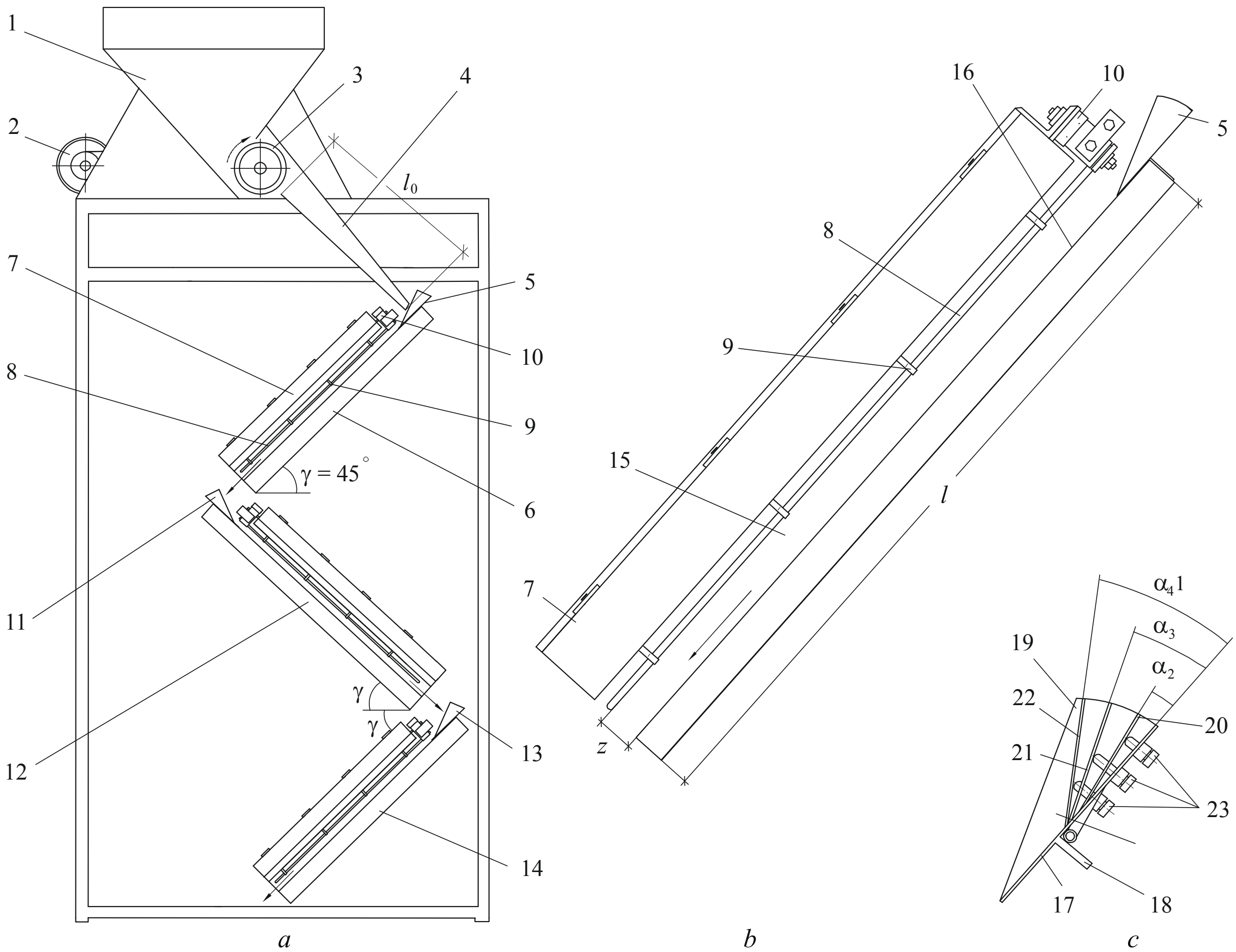

Figure 1. Modular launch furnace:
a – modular launch furnace; *b* – firing module; *c* – accelerating tray

There are the accelerating trays (Figure 1, 2) in the upper part of each module. They consist of a base plate 17, a stop 18 with side walls 19 and a set of hinged plates 20–22. The inclination angles of hinged plates α_2, α_3, and α_4 can be adjusted using screws 23.

The dispenser drum is made with longitudinal grooves 24–26, step-variable in depth (Figure 2). In this case, the greatest depth is at the grooves 24 located above the central plate 22 of the accelerating tray. There are adjacent grooves 25 above the plates 21. They have a shallower depth. The further from the center the grooves are located, the shallower their depth:

$$t_4 > t_3 > t_2 > t_1.$$

The number of plates of the accelerating tray and the number of grooves may be different, depending on the width of the refractory surface of module *B* and the temperature distribution on the electric heaters. Moreover, the length of the grooves on the drum b_1, b_2, b_3, and b_4 and the width of the plates of the accelerating tray can also be different.

Vermiculite concentrate particles falling on plate 22 in Zone 4 (Figure 2) acquire the maximum initial velocity v_{04x} due to the larger angle of its inclination α_4. In this regard, their average local velocity in this zone will be greater than in the side zones 1, where the plates have a zero inclination angle. If the speed of particles is maximum here, then the time of their movement is minimal, and the local productivity is proportional to the speed and is maximum in comparison with other zones. In Zone 4 the electric heaters are hottest.

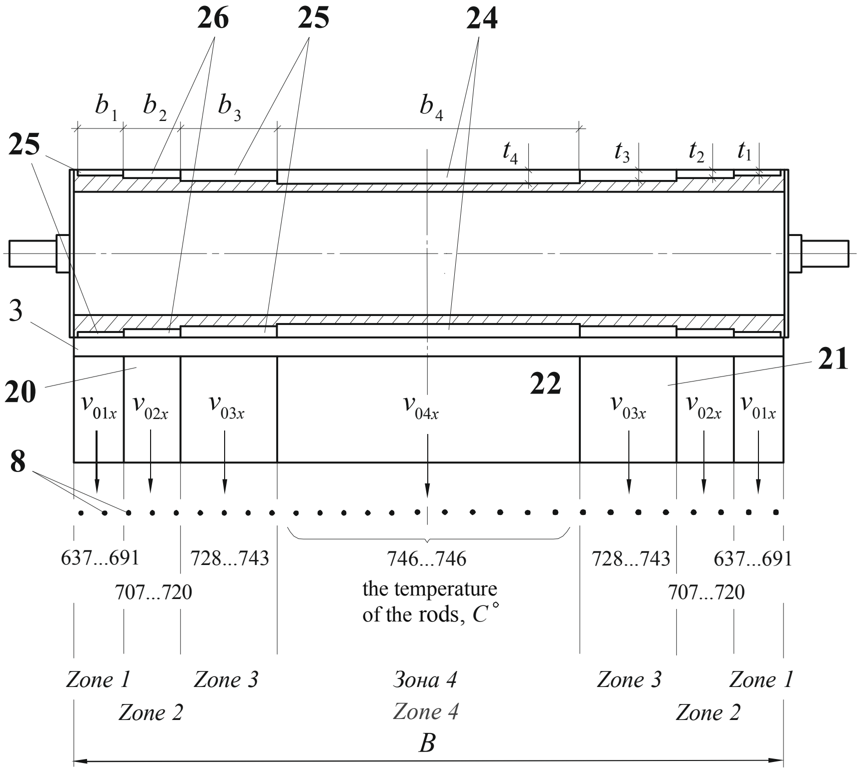

Figure 2. Dispenser drum, accelerating tray and electric heater rods with indication of temperature zones

In Zone 3, the temperature of the electric heaters is lower, therefore, the concentrate particles falling on plates 21 (Figure 2) should receive a lower initial velocity v_{03x}. It is due to their smaller tilt angle α_3. The local productivity in these zones is proportional to the average local speed of the particles, and the particles motion time is slightly longer than in the central zone. The same applies to Zone 2 and 1: the average local particle speeds from the central to the side zones should become less and less, as the temperatures of the heaters decrease from the center to the periphery.

Adjusting screws 23 (Figure 1) allow to change the initial and the average local speeds when one size group of vermiculite concentrate change into another, since larger expanded grains move at higher speeds than small ones (proofed by the tests).

Due to the accelerating trays such distribution of average local speeds over the temperature zones is created, that in each zone vermiculite will consume the necessary amount of thermal energy during the corresponding time and, at the same time, the whole will be fully expanded. If this distribution is carried out correctly, the productivity of the furnace will increase with constant energy consumption.

The initial velocities v_{01x}, v_{02x}, v_{03x}, and v_{04x} determine the average particles local speeds in the corresponding zones and depend on the inclination of the accelerating plates. However, they also depend on the speed of particles falling onto these plates. Figure 3 demonstrates the change in the vectors of the initial speeds at different angles of inclination. There is a vector v_f denoting the falling speed in each triangle of speeds. If the falling speed for the places of junction of modules 6 and 12 and modules 12 and 14 (Figure 1) is determined by their length *l*, then it is necessary that the speed v_f at the place of junction of the tray 5 and the upper module 6 is the same.

The joint operation of the dispenser and the upper module of the furnace, which provides the balance of the supplied concentrate and the furnace productivity, will be discussed below. Let us consider the issue of the correct distribution of local speeds over the module zones.

Local speeds distribution

The interaction between the thermal energy absorbed by vermiculite, leading to its structural change, the loss of hydrated water and a multiple decrease in density, and radiant energy falling on the vermiculite grains from the surfaces of the electric heater rods was discussed in the research [13].

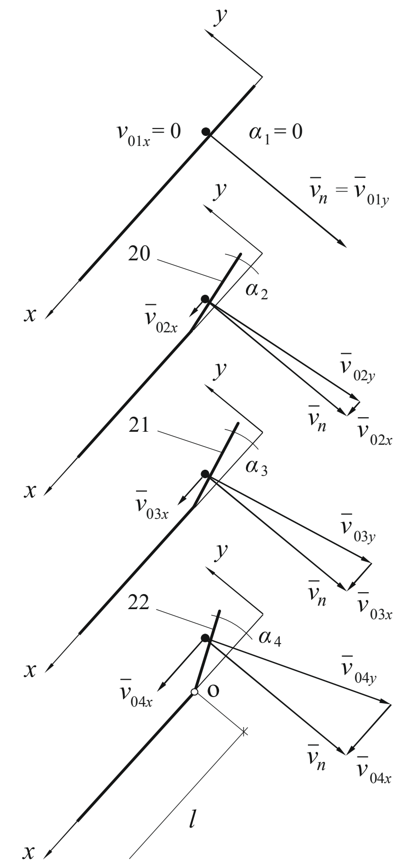

Figure 3. Speeds triangles on the plates of the accelerating tray at different values of the inclination angle of its plates

Let us use the obtained dependence for the heat power flux θ absorbed by the expanded material (W):

$$\theta = 0.667 \cdot \alpha \cdot \sigma \cdot T^4 \cdot s \cdot \varepsilon \cdot (1 + \rho \cdot \varphi_{12})(2 \cdot \varphi_{1v} + \varphi_{2v}), \quad (1)$$

where α – is the capacity of vermiculite absorbability (0.768); σ – Stefan-Boltzmann constant, 5.67, W/m^2 K; T is the surface temperature of the heater rods, K; s is the area of all surfaces of the heater rods in three furnace modules, m^2; ε – the nichrome blackness degree (0.96); ρ is the nichrome reflectivity (0.04); φ_{12}– is the angular coefficient of heat fluxes from one rod to another, φ_{1v} is the angular coefficient for rods located on both sides symmetrically relative to the vermiculite grain; φ_{2v} – is the angular coefficient for rods located on both sides with relative to the vermiculite grain which is in contact with one of the rods [13].

The above formula (1) does not take into account the effect of reflected radiant fluxes from the refractory base of the module and its cover. The same Ref. [13] states that it was proofed by the tests that the thermal power of the reflected fluxes is 10...12% of the heating power of furnace systems.

The absorbed thermal power θ provides complete expanding of the material and it is unchanged for any thermal zone of the module. Therefore, we can write the equality valid for the i-th number of zones (J):

$$E = \theta_1 \cdot t_1 = \theta_2 \cdot t_2 = \theta_3 \cdot t_3 = \theta_4 \cdot t_4 = \theta_i \cdot t_i, \quad (2)$$

where E is the energy of vermiculite heat absorption, sufficient for full expanding, J; t_1 is the average local time of vermiculite flow movement in Zone 1 (Figure 2), equals to the time of firing in the furnace, adopted as an analogue [14–16]; t_2, t_3, t_4, and t_i are the average local times of vermiculite flow movement in other thermal zones, *s*.

To find the value of the vermiculite time of movement in the zones, it is not required to determine the energy *E*. We use the ratios, in this case for four zones, based on formula (2):

$$t_2 = \frac{\theta_1 \cdot t_1}{\theta_2 \cdot t_2},\ t_3 = \frac{\theta_1 \cdot t_1}{\theta_3 \cdot t_3},\ t_4 = \frac{\theta_1 \cdot t_1}{\theta_4 \cdot t_4}. \tag{3}$$

The average values of rods of electric heaters heating temperatures by zones (Figure 2):

- in Zone 4 – 1030 °K;
- in Zone 3 – 1019 °K;
- in Zone 2 – 986 °K;
- in Zone 1 – 940 °K.

Since in formula (1) only temperature changes for each zone, then the relations (3) will take the form (s):

$$t_2 = \frac{T_1^4}{T_2^4} t_1,\ t_3 = \frac{T_1^4}{T_3^4} t_1,\ t_4 = \frac{T_1^4}{T_4^4} t_1, \tag{4}$$

where T_1, T_2, T_3 and T_4 are the average temperatures of the heater rods in the corresponding zones.

Taking the time t_1 = 0.91 s and the average speed v_m = 1.05 m / s with a module length of 0.95 m for the adopted analogue – a prototype furnace [15], from relations (4) we obtain the time of vermiculite movement in thermal zones (Figure 2) (s):

$$t_2 = 0.82 \cdot t_1,\ t_3 = 0.75 \cdot t_1,\ t_4 = 0.72 \cdot t_1.$$

It follows from the found relationships that the time of vermiculite particles movement through Zones 2, 3, and 4 in the furnace modules should decrease by 17.9%, 24.9%, and 27.8%, respectively, in comparison with the first zone.

The average time of vermiculite being in a prototype furnace (furnace time constant) is 2.74 s [16]. The indicated values t_1 = 0.91 s and v_m = 1.05 m / s correspond to Zone 1 of the considered furnace (Figure 2), and for Zones 2, 3, and 4 the average time of local flows should be:

$$t_2 = 0.747 \text{ s},\ t_3 = 0.683 \text{ s},\ t_4 = 0.657 \text{ s}.$$

The l/t_i ratio determines the corresponding average local flow rates of vermiculite in thermal zones:

$$v_{m2} = 1.27 \text{ m/s},\ v_{m3} = 1.39 \text{ m/s и } v_{m4} = 1.45 \text{ m/s}.$$

It is necessary to find such values of the initial particles' speeds on the plates of the accelerating tray, at which the required average speeds will be achieved. Taking into account that gravity and friction forces act on each particle, and neglecting the air resistance, we write the differential equation:

$$m\frac{d^2x}{dt^2} = m \cdot g \cdot \sin\gamma - m \cdot g \cdot f \cdot \cos\gamma, \tag{5}$$

where γ is the inclination angle of the modules (Figure 1); *f* is reduced coefficient of sliding–rolling friction, determined by the tests, *f* = 0.51 [16]; *m* is the particle mass.

Separating the variables in equation (5), we get (m/s):

$$v_x = g\left(\sin\gamma - f\cos\gamma\right)t + v_{0x}, \tag{6}$$

where v_x is the final particle velocity in the zone (the same as the falling velocity v_f) corresponding to its time (t_1, t_2, t_3 and t_4), v_{0x} is the initial particle velocity on the corresponding plates of the accelerating tray (Figure 3).

Let us determine the final falling velocity for the first zone using the formula (6), taking into account the fact that v_{01x} = 0 m/s:

$$v_f = 9.81 \cdot (0.707 - 0.51 \cdot 0.707) \cdot 0.91 + 0 = 3.1.$$

Setting the same falling velocity (3.1 m/s) for all other zones, we determine the initial local velocities using expression (6) (m/s):

$$v_{0x} = v_n - g\left(\sin\gamma - f\cos\gamma\right)t. \quad (7)$$

Substituting the movement time in the zones (t_2 = 0.747 s, t_3 = 0.683 s, t_4 = 0.657 s) into formula (7), we determine the initial velocities, (m/s):

- in Zone 2 – v_{02x} = 0.56;
- in Zone 3 – v_{03x} = 0.78;
- in Zone 4 – v_{04x} = 0.87.

In accordance with the vector diagrams (Figure 3), we obtain the relations that determine the angles sines:

$$\sin\alpha_2 = \frac{v_{02x}}{v_f} = \frac{0.56}{3.1} = 0.18,\ \sin\alpha_3 = \frac{v_{03x}}{v_f} = \frac{0.78}{3.1} = 0.26,\ \text{и}\ \sin\alpha_4 = \frac{v_{04x}}{v_f} = \frac{0.87}{3.1} = 0.28.$$

The angles themselves at which the required initial speeds and average local speeds of vermiculite particles in the thermal zones of the furnace modules will be provided equal: α_2 = 10.5 °, α_3 = 15 ° and α_4 = 16.5 °.

As already noted, when processing other size of groups of vermiculite concentrates, it is necessary to change the average local rates. For this purpose, the adjusting screws 21 are provided in the accelerating trays of the modules. By using the adjusting screws, the tilt angles of the plates 18–20 can be changed (Figure 1). When firing smaller concentrates, the time of vermiculite passage should decrease, and therefore, it is necessary to increase the angles α_2, α_3 and α_4 in order to increase the average local speeds in the corresponding thermal zones.

Figure 4 illustrates a nomogram for determining the inclination angles of the plates of the accelerating tray at a given local speed.

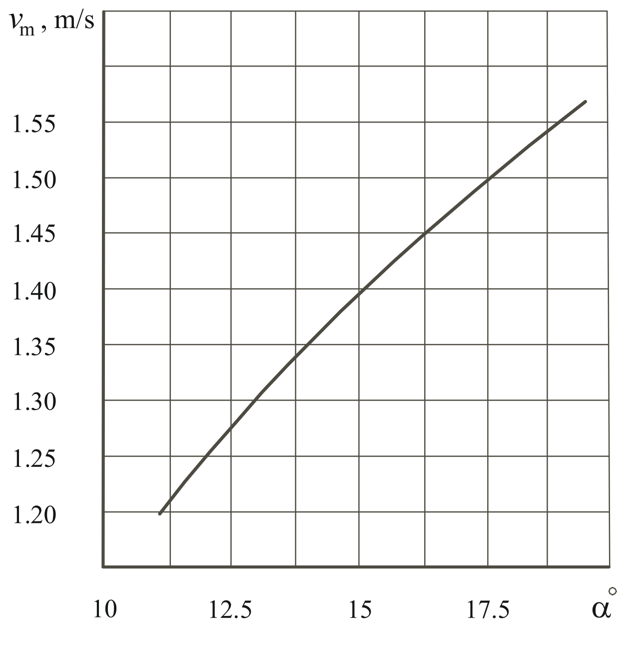

Figure 4. Nomogram for determining the inclination angles of the plates of the accelerating tray at a given average local speed in the thermal zones of the module

Joint operation of the dispenser and furnace modules

To provide a balance between the vermiculite concentrate amount supplied by the dispenser and the amount of expanded material passing through the furnace modules, two conditions must be met:

- the rate of concentrate particles falling out from the inclined tray 4 (Figure 1) should provide the same initial speeds in the thermal zones on the accelerating tray of the upper module, as in the accelerating trays 11 and 13 of the middle and lower furnace modules;

- the capacity of the dispenser for concentrate must correspond to the full capacity of the furnace for expanded material, taking into account the expansion coefficient.

To meet the first condition, it is necessary to find the length value of the inclined tray l_0, at which the rate of the concentrate particles falling out of it will provide the same initial speeds on the accelerating tray of the upper module as on the accelerating trays 11 and 13 of the middle and lower furnace modules. In this case, the friction coefficient f_0 in equation (5) will have a value of 0.68 [15], since flat particles of vermiculite mica slide over steel and there is no rolling, as on refractory surfaces of modules.

From expression (6), which in this case will have the form:

$$v_f = g\left(\sin\gamma - f_0\cos\gamma\right)t + v_{0x},$$

Let us find the time t required for the particles to reach the velocity v_f = 3.1 m/s at the moment of contact with the plates of the accelerating tray 5 (Figure 1) at zero initial velocity v_{0x}:

$$t = \frac{v_n}{g\left(\sin\gamma - f_0\cos\gamma\right)} = 1.4 \text{ m/s.} \quad (8)$$

To find the length of the dispenser tray 4 (Figure 1), we fulfill the second integration of equation (5):

$$l_0 = \frac{1}{2}g\left(\sin\gamma - f_0\cos\gamma\right)t^2 + v_f \cdot t, \quad (9)$$

where t is the convergence time of particles along the tray, determined by expression (8); γ is the inclination angle of the tray to the horizon, 45 °.

To supply the concentrate by the dispenser to the furnace in accordance with the capacity of the furnace for expanded material, we will use the formula [17–22]:

$$P_G = \frac{P_V}{k},$$

where k is the expanding coefficient depending on the size group of the —vermiculite concentrate and the natural hydration of the mica (Figure 5).

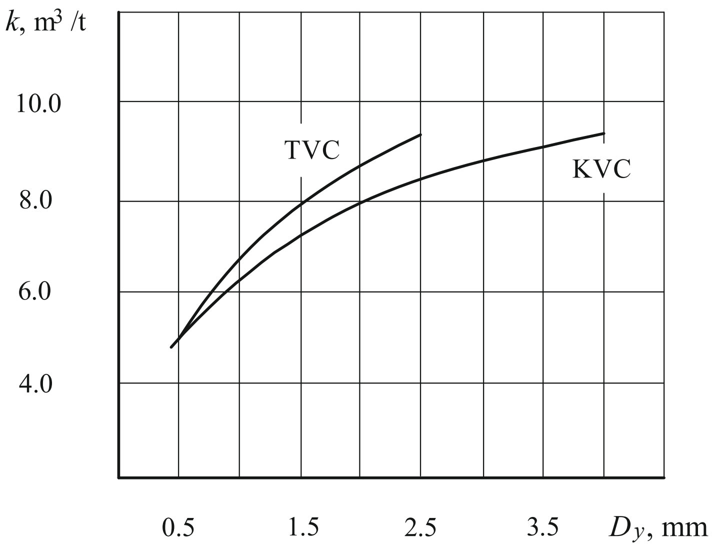

Figure 5. The dependence of the expanding coefficient on the nominal concentrate particle diameter for two fields – Kovdorskoye (KVC) and Tatarskoye (TVC)

Conclusions

Determination of the local capacities and the total furnace productivity.

With the width of the modules B = 95 cm, as in the prototype furnace [15], the productivity of the furnace without accelerating trays 5 (Figure 1) on vermiculite concentrate, for example, grade KBK-4 (4 is the conventional average particle diameter), is equal to 0.75 m^3/hour. Then the hourly productivity, reduced to the unit of width, will be equal to, (m^3/cm·hour):

$$P_h = \frac{0.75}{95} = 0.0079.$$

Since the local average speeds in zones No. 2, No. 3, and No. 4 the increase relative to the first zone will be:

- at $\frac{1.27}{1.05} = 1.21$ times or by 21 %;
- at $\frac{1.39}{1.05} = 1.32$ times or by 32 %;
- at $\frac{1.45}{1.05} = 1.38$ times or by 38 %;

then the local capacities, taking into account the width of the zones B_4 = 21 cm, B_3= 15 cm, B_2 = 12 cm and B_1 = 10 cm (Figure 2) will be equal to, ($м^3$/h):

- in the fourth zone: P_4 = 0.0079·21·1.38 = 0.229;
- in two third of zones: P_3 = 2·0.0079·15·1.32 = 0.313;
- in two second zones: P_2 = 2·0.0079·12·1.21 = 0.229;
- in two first zones: P_1 = 2·0.0079·10·1.0 = 0.16.

The total furnace productivity will be, (m^3/h):

$$P = 0.229 + 0.313 + 0.229 + 0.16 = 0.931.$$

The increased productivity of the modular–launch furnace due to the distribution of the speeds of the vermiculite flows movement over the thermal zones of the modules is equal to 0.931 m^3/h, which is 24% more than that of the experimental industrial furnace taken as a prototype. Moreover, the energy consumption does not grow and the specific energy consumption of the process increases by the same 24%.

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Электрлендірілген модульдер аймақтарында өңделетін шикізат ағыны жылдамдығының таралуын реттейтін жылу агрегаты

Ісінген вермикулитті өндіру және пайдалану технологиялары саласындағы зерттеулер өзекті болып табылады. Көмірсутекті отынмен жұмыс істейтін отты пештерге балама ретінде вермикулитті жағуға арналған электр пештерін әзірлеу белсенді жүргізілуде. Бұл пештерде ісінген бөлшектердің ағындары бақыланбайтын және бөлшектердің ауырлық күшінің әсерімен анықталады. Мақалада пайдалану кезінде пайда болған агрегаттардың кемшіліктерін жойғаннан кейін модульдік-іске қосу түріндегі жылу агрегаттарында вермикулит концентраттарын термиялық өңдеу мүмкіндігі қарастырылған. Электр жылытқыштар мен күйдіру модульдерінің отқа төзімді бетінің температурасы көлденеңінен біркелкі бөлінбейтіні байқалды: температура орталықтан периферияға дейін айтарлықтай төмендейді. Бұл ерекшелік техникалық шешімді көрсетті – ісінген вермикулиттің жалпы ағынын пеш модульдерінің жылу аймақтары арасындағы жергілікті және бақыланатын ағындарға олардың температурасын ескере отырып бөлу. Жергілікті вермикулит ағындарының жылу сыйымдылығын салыстыру арқылы әр жылу аймағындағы бөлшектердің қажетті қозғалыс уақыты, сондай-ақ көрсетілген аймақтардағы олардың қозғалысының орташа жергілікті жылдамдығы белгілі. Жергілікті шығындар есебі жүргізілді және жаңғыртылған пештің жалпы өнімділігі анықталды. Жаңартылған пештің өнімділігі тәжірибелі пешке қарағанда 24 % жоғары. Өнімділіктің жоғарылауымен, бірақ электр энергиясын тұтынумен бірдей, күйдіру процестерінің энергия шығыны 24 %-ға төмендегені көрсетілді. Бұл пешті жетілдіреді және бәсекегеқабілетті етеді. Мақалада зерттеу процесін суреттейтін және осы ғылыми жұмыста қойылған мақсатқа қол жеткізуді растайтын диаграммалар келтірілген.

Кілт сөздер: электр модульдік-іске қосу пеші, күйдіру модулі, температураның біркелкі бөлінбеуі, температуралық аймақтар, үдеткіш науа, жылытқыштар, жылу қуаты, орташа жергілікті жылдамдық, жергілікті өнімділік, жалпы өнімділік.

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Тепловой агрегат с регулируемым распределением скоростей потока обрабатываемого сырья в зонах электрифицированных модулей

Исследования в области технологий производства и использования вспученного вермикулита являются актуальными. Активно ведутся разработки электрических печей для обжига вермикулита, как альтернатива пламенным печам, работающим на углеводородном топливе. В данных печах потоки расширенных частиц неконтролируемы и определяются действием сил тяжести частиц. В статье рассмотрена возможность термической обработки вермикулитовых концентратов в тепловых агрегатах модульно-пускового типа после устранения недостатков агрегатов, возникших в процессе эксплуатации. Было замечено, что температура электронагревателей и огнеупорной поверхности обжиговых модулей распределяется неравномерно по горизонтали: температуры значительно снижаются от центра к периферии. Эта особенность показала техническое решение – разделение общего потока вспученного вермикулита на локальные и контролируемые потоки между тепловыми зонами модулей печи с учетом их температур. Путем сравнения теплоемкостей локальных потоков вермикулита определяли требуемое время движения частиц в каждой тепловой зоне, а также средние локальные скорости их движения в указанных зонах. Проведены расчеты локальных расходов, и определена общая производительность модернизированной печи. Производительность модернизированной печи на 24 % выше, чем у опытной печи. Показано, что при увеличении производительности, но равном потреблении электроэнергии, удельное энергопотребление процессов обжига уменьшается на те же 24 %. Это делает печь более совершенной и конкурентоспособной. В статье приведены диаграммы, иллюстрирующие процесс исследования и подтверждающие достижение цели, которая поставлена в данной научной работе.

Ключевые слова: электрическая модульно-пусковая печь, обжиговый модуль, неравномерное распределение температуры, температурные зоны, ускорительный лоток, нагреватели, тепловая мощность, средние локальные скорости, локальная производительность, общая производительность.

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