

TECHNOLOGICAL AND ENERGY CAPABILITIES OF ELECTRIC TWO-MODULE POURING FURNACES WITH UPPER HEATING SYSTEM

A. I. Nizhegorodov^{1,2}

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A new modified two-module electric modular-pouring furnace with an upper heating system of heaters and an additional “zero” (non-electrified) module is considered. By eliminating the lower third firing module, a reduction of energy consumption by a third compared to the three-module prototype furnace was achieved. Suspended emitting elements, which are not only energetically more efficient than the previous ones made of strip heaters, but also constructively provide double the furnace throughput due to the suspension under thermal covers, are used in the modules. This leads to a doubling of its performance. Altogether, it gives a decrease in the specific energy consumption of vermiculite firing in a new two-module furnace to a level of 50.4 J/m³.

Keywords: two-module electric furnace, upper heating system, suspended emitting elements, furnace throughput, energy intensity.

INTRODUCTION

The concept of electric modular-pouring furnaces for firing vermiculite was realized in 2003; the first article [1] about it was published in 2007. The use of imperfect two-three-module furnaces at the Irkutsk enterprise Kvalitet showed that in terms of specific energy intensity (240 – 250 mJ/m³) they exceeded the fired furnaces on hydrocarbon fuel, that were used for these purposes [2]. Further improvement of this concept went through six-module furnace designs (235 mJ/m³) with series-parallel integration of modules (196 mJ/m³) [3] and, finally, a furnace appeared, that had an additional “zero” module that did not contain a thermal radiation source [4] and that was very efficient from the energy point of view [5].

For manufacturing foamed vermiculite in these furnaces, a heating system with a lower arrangement of radiant energy emitters was used. The heating system consisted of series-connected U-shaped heaters extended along the firing modules, laid on the refractory surfaces of the modules and forming longitudinal chambers with walls made of strip nichrome with a height of 8 – 10 mm. It was one of the reasons

for the transition to an alternative concept of more complex furnaces with movable hearth platforms [6], since in the zones where the foaming vermiculite was poured from one module to another, crowding of grains, which packed into 2 – 3 rows and overlapped the height of the strip heaters, generated. It led to overheating and heaters blowing due to a sharp decrease in heat removal from them in these zones. Attempts to increase the performance of modular-pouring furnaces at the expense of a greater supply of raw materials led to the failure of furnace units; therefore, their performance P_V was 1.5 – 1.75 m³/h for different types and sizes of vermiculite concentrate grains.

The transition from the lower heating system with strip heating elements to the upper one (suspended from wire nichrome), located not on the refractory module surface, but above it, fixed under the module thermal cover, made it possible to solve the problem of limiting the vermiculite concentrate supply to the furnace.

The objective of this study was to increase the performance of modular-pouring furnaces at least 2 times in comparison with the prototype furnace due to the application of heating systems with an upper arrangement of radiant energy emitters in firing modules and organizing the vermiculite movement in a denser flow in them.

¹ Irkutsk National Research Technical University, Irkutsk, Russia.

² nastromo_irkutsk@mail.ru

CONSTRUCTIVE FEATURES OF THE INITIAL AND NEW MODULAR-POURING FURNACES

Figure 1 shows the diagrams of electric modular-pouring furnaces: the initial three-module concept (prototype furnace) and a new modified modular-pouring furnace, both with an additional “zero” (non-electrified) module. Furnace units (see Fig. 1*a, b*) have the same batchers of vermiculite concentrate 1 with laying chutes 2, from which the raw material, as the drums rotate, is poured into the feeding zone onto the surface of the upper firing modules 3. Vermiculite concentrate moves under the action of gravity of particles in a closed space formed by refractory bases of modules 3 and thermal covers 4, pouring from one module to another with a velocity loss and a subsequent acceleration on the module located below. This discretely accelerating movement is uncontrollable; it leads to generating of vermiculite particles (grains) crowding in the pouring zones and the appearance of ever-increasing intervals between them as they accelerate and move to the lower edges of the modules. It was one of the limitations of increasing the performance and, in general, improving the modular-pouring furnaces. But an upper suspended heating system was developed, which consists of series-connected electric heaters made of wire nichrome, held by fastening heads 5 (see Fig. 1*b*) and hooked onto the thermal cover 4 by eyebars 5 located along the heating elements 6 (Fig. 2) [8]. The heating system made it possible to remove largely the limitation on the raw materials supply by the batcher and increase the furnace throughput.

For the operation of “zero” additional modules 7 (see Fig. 1), suction devices 6 of hot air coming out from under the thermal covers 4 are used [4, 5]. To reduce heat losses, the firing modules in the new furnace are placed between thermally insulated removable panels 8. In the zone of pouring from the upper module to the lower one, a baffle 9 is installed in order to reduce the velocity, the baffle forces the foaming vermiculite to accelerate again on the lower module, which increases the total duration of firing. Inside the “zero” module, there are heat chambers, through which hot air penetrates with the help of an exhaust fan (not shown in Fig. 1), providing its heating to complete the vermiculite dehydration without losses of exergy accumulated in foamed grains [4] (see Fig. 1, arrows “Towards the exhaust”).

In the initial three-module prototype furnace (see Fig. 1*a*), a lower heating system, which consisted of U-shaped strip emitters connected in an electric circuit, fastened only on heads 5 and forming longitudinal chambers with walls with 8 – 10 mm height, was used. The upper heating system made of wire emitting elements is shown in Fig. 2 in a horizontal position. Between the refractory base 1 and the thermal cover 2, covered with mullite silica felt 3 and made of a ceramic-vermiculite plate [8], there are electric emitters of radiant energy 6 fastened on the heads 4 and eyebars 5 with a gap a to the thermal cover and the gap b to the refractory base. A flow of vermiculite particles or grains, depending on their foaming degree, moves under the heaters.

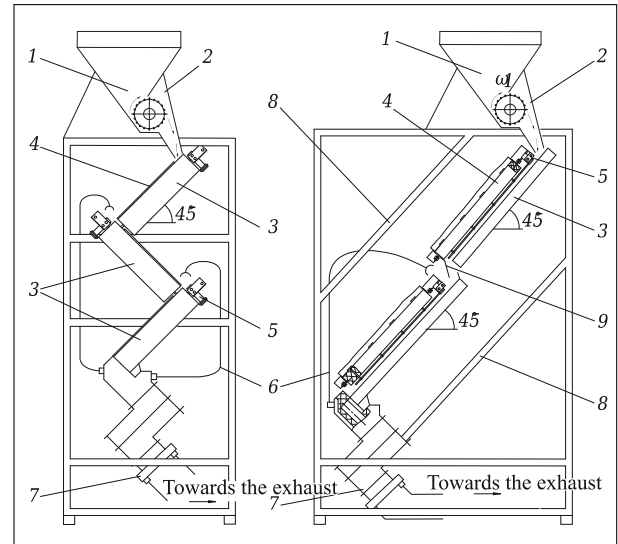


Fig. 1. Modular-pouring furnaces of the initial concept (*a*) and the new modified one with an upper heating system and two electrified firing modules (*b*).

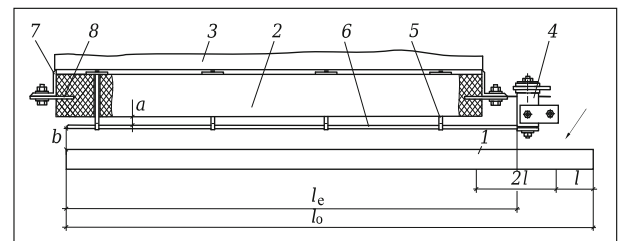


Fig. 2. Upper heating system of the new modified furnace.

The thermal cover is edged with a metal angle 7 and is held by fasteners 8, and in order to eliminate conductive heat drain through the eyebars 5, it is covered with felt 3 on top.

VERMICULITE IN POURING ZONES OF MODULES WITH DIFFERENT HEATING SYSTEMS

As noted above, in the zones where vermiculite was poured from module to module, its grains due to zero velocity along the module axis created at least a two-row layered structure. Figure 3 shows the regular structure (model) of a two-layer array of identical grains in fragments of cross-sections of modules with a lower heating system (Fig. 3*a*). The grains are bounded by walls made of strip nichrome with a thickness s , forming operating chambers of width r with an upper heating system (Fig. 3*b*), in which the grains are not constrained by the walls.

In modules with a lower heating system, in case of an excessive raw materials supply and a two-layer grains arrangement, thermal radiation in the pouring zones ran into an ob-

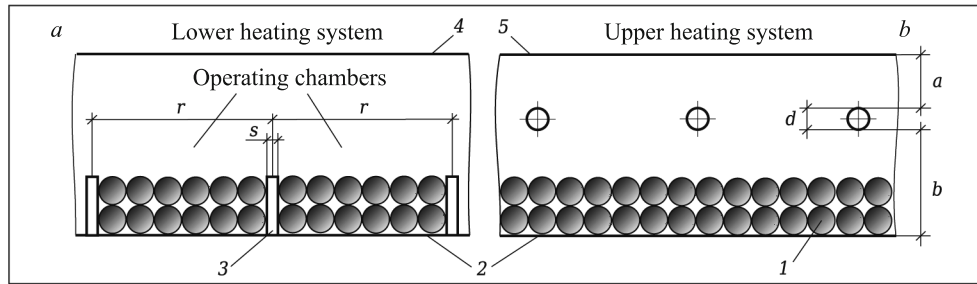


Fig. 3. Fragments of the cross-sections of the firing modules with heating systems made of surface strip heaters (a) and suspended wire heaters (b).

struction made of thermal insulating vermiculite, which led to a rapid local nichrome overheating, blowing and furnace failure. Therefore, the desire to increase the supply and performance of the furnace was limited by values P_V mentioned above.

In modules with an upper heating system made of wire heaters (see Fig. 3b), in case of an excess supply and a two-layer grains arrangement, thermal radiation does not close inside the chambers, since there are simply no chambers in this case, but falls onto the two-layer array from above. The upper grains (or flat particles of concentrate in the zone of their pouring onto the upper module from the batcher) begin to foam, although they partially cover the underlying particles from radiation.

But there are no conditions for local overheating of the emitters in this case, and therefore the raw materials supply and, consequently, the performance of the furnace can be increased.

FEATURES OF MATERIAL MOVEMENT IN POURING ZONES AND IN ADJOINING SECTIONS

Let us consider the grains movement in a module at their initial two-layer arrangement in the pouring zone, followed by a transition to a single-layer arrangement in the lower section (Fig. 4).

Let us suppose that initially the pouring zone with a two-layer arrangement of grains has a length l in the upper part of the module (see Fig. 4). Inside the marked rectangle, the grains occupy a height of $2D$. The lower grains under point b begin to roll out at an accelerated rate, while the upper ones under point a do not move yet. In the section of module $2l$ (see Fig. 4), all the grains are already arranged in one layer without gaps between them, while the grains under point b already have a certain velocity, and the grains under point a are just starting to move. A transition from a two-layer regular grains structure to a single-layer one occurs. Below point b , the grains begin to roll out at an accelerated rate, moving further and further apart from each other, but with their double concentration on the refractory base l (see Fig. 2).

In the initial experimental-industrial prototype furnace [7], the design parameters of the firing modules of which will be taken as basic, the total length of the refractory surface l_r was 0.95 m and was equal to its width $B = 0.95$ m. At that, the length l_e of the part of the module refractory surface covered with strip electric emitters was 0.9 m, and the pouring zone, into which vermiculite enters, falling from the module located above, had a length of $l = 0.05$ m.

In further calculations, the same dimensions will be taken in order to obtain a more accurate result when comparing the options. For this, the design of the module with the upper heating system should have some reference dimensions, as shown in Fig. 2. If the length of the zone l (see Fig. 4b) is, as in the prototype, 0.05 m and the grains in it are arranged in two layers, then in time t on the section of module $2l$, which is 0.1 m long (see Fig. 4a and Fig. 2), the grains in the thermal field of electric heaters δ will be rearranged into one layer (see Fig. 2). Therefore, due to section $2l$, the total length of the refractory surface l_r will now increase to 1.05 m, and the length l_e of the emitting part of the heating elements will be 0.9 m, same as in the prototype. Thus, only the length of the refractory surface l_r changes, while the length of covering the vermiculite flow with heat radiation l_e remains the same. Starting to move from point a (see Fig. 4a), each grain will travel a path equal to $l_r - l$, that is, 1.0 m.

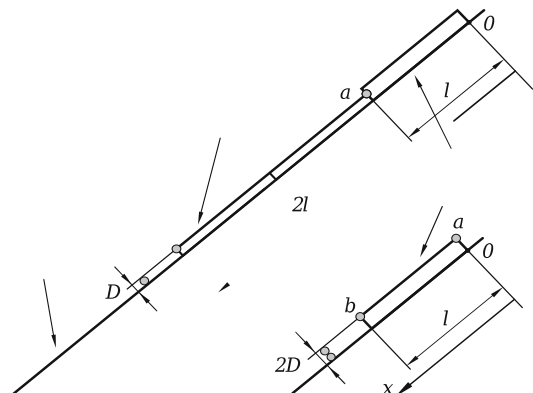


Fig. 4. Illustration of the transition from a two-layer grain structure to a single-layer one.

The results of the study of the vermiculite flow dynamics are given in paper [7]; therefore, the authors will use the ready-made solutions and determine the time t_r of the movement of foamed (rolling) grains in modules:

$$t_r = \sqrt{2(l_0 - l) / g \sin \alpha - \frac{\mu}{R} \cos \alpha}, \quad (1)$$

where α is the inclination angle of the module, deg.; g is the acceleration of gravity, m/s^2 ; μ/R is the relative coefficient of rolling resistance of vermiculite grains (dimension of μ is meter), determined experimentally [7] and equal to approximately 0.32; R is the average rolling radius, m.

In [9] it is shown that the time of movement (sliding) of flat non-foamed particles in the upper module is approximately 10% of the total duration of vermiculite movement in a three-module prototype furnace (2.74 sec is the time constant of the furnace [7]). It can be neglected and the time can be calculated according to Eq. (1), which gives the total time of the flow passage through two modules = 1.3 sec. But this calculation is done for spherical bodies. The anisotropy of the shape of vermiculite grains, which do not have spherical symmetry, increases the movement time by about 40%, as it was shown by experiments with an experimental-industrial furnace [7]. Therefore, a correction factor of 1.4 should be introduced into Eq. (1), and then the time of the flow passage in the two-module furnace t_{Σ} (see Fig. 1b) will be equal to 1.82 sec.

Let us turn to the results of determining the bulk density ρ of foamed vermiculite from Kovdor concentrate KVK-4 in an experimental-industrial three-module furnace of the initial concept (see Table 1) [7]. In the first (upper) module, ρ decreases from 540 to 126 kg/m^3 , and 33% of the furnace heat power is spent on this; in the second module it changes from 126 to 94 kg/m^3 , but even this insignificant additional foaming also takes a third of the power. The third module, consuming the same 33% of the power, changes ρ by only 8 kg/m^3 . Obviously, this is far from a rational furnace design.

According to data of Table 1, a graph of dehydration and ρ loss of vermiculite of the Kovdor deposit during its firing in a furnace is constructed (Fig. 5). In an experimental-industrial three-module prototype furnace, the passage time of the foamed vermiculite grains was about 2.74 sec and the foamed material density of approximately 86 kg/m^3 was achieved [7]. The modified two-module furnace in a time of 1.82 sec is capable of passing twice as much vermiculite (due to the two-layer filling of the pouring zones) and obtaining at the output the density, which is only 9% higher, i.e. 94 kg/m^3 (see Fig. 5), while consuming power by a third less. These missing 8 kg/m^3 will be made up by the “zero” module 7 (see Fig. 1b), which has been proved experimentally [5].

However, the possibility of doubling the performance and significantly reducing the specific energy intensity of the process must be proven. Will the power of the heating sys-

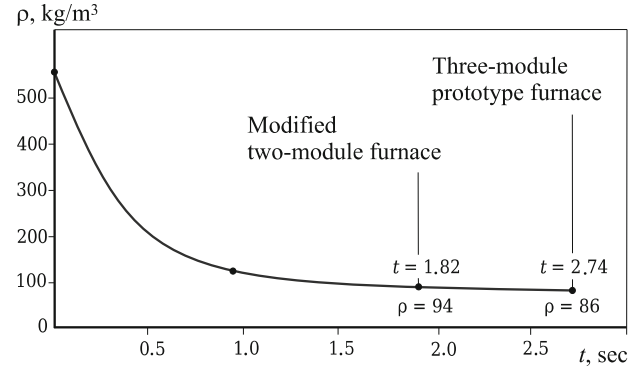


Fig. 5. Graph of dehydration and bulk density loss of vermiculite

tems of the two modules be enough to provide full heat absorption and foaming of such a dense vermiculite flow in 1.82 sec?

ENERGY ANALYSIS OF THE FIRING PROCESS IN MODULES WITH UPPER HEATING SYSTEM

When studying the process of heat absorption of vermiculite in the thermal field of the firing modules of pouring furnaces, it was assumed that by the time it leaves the furnace, the mass of foamed vermiculite is heated to the temperature of electric emitters; the calculations gave the values of the absorbed heat θ_i on average 1210 kJ/kg for Kovdor concentrates [7, 10]. Recent experiments on a physical full-scale model of an electric furnace with a movable hearth platform showed that when the minimum vermiculite density of 90–92 kg/m^3 was reached, the mass of foamed material reached a temperature of approximately 512°C, and the temperature of the emitting nichrome surfaces was from 718 to 776°C in different points with an average value of 747°C [11]. Such a significant discrepancy led to the need to recalculate the balance equation for specific thermal energies:

- the dehydration energy of the mineral remains the same: $\theta_x = 196.9$ kJ/kg [7];

- the energy accumulated by the dry mass of the foamed grains has decreased: $\theta_c = ck_{\tau}m0.816\Delta T = 860 \times 1.23 \times 1 \times 0.806(512 - 100) = 349.8$ kJ/kg, where c is the average heat capacity of vermiculite concentrates, $c = 860$ J/(kg·°C)

TABLE 1. Distribution of the Vermiculite Bulk Density in the Process of its Movement in the Furnace

Module (from top to bottom)	Density of material, kg/m^3		Density change in the module $\Delta\rho_m$, kg/m^3
	ρ_{in} at the module input	ρ_{out} at the module output	
First	540	126	414
Second	126	94	32
Third	94	86	8

[12]; k_T (1.23) is the coefficient that takes into account the increase in the specific heat capacity of a mineral with an increase in temperature [13]; m is the mass of the concentrate (1 kg); 0.806 is the proportion of the solid phase [7]; $(512 - 100^\circ\text{C})$ is the temperature difference ΔT , where 100°C is the temperature of the pre-heated concentrate before supplying into the furnace;

– the heat of the phase transition of chemically bound and interlayer water at 100°C remains the same: $\theta_w = 258.8 \text{ kJ/kg}$;

– the energy of water vapor overheating will decrease: $\theta_v = c_v m 0.115 \Delta T = 1593.4 \times 1 \times 0.115 \times (512 - 100) = 75.5 \text{ kJ/kg}$, where c_v is the average specific heat capacity of water vapor in the range from 100 to 500°C , which is approximately $1593.4 \text{ J/(kg}\cdot^\circ\text{C)}$ [14];

– the heat of the adsorbed carbon dioxide heating will decrease and will be equal to:

$$\theta_{\text{a.c.}} = c_{\text{CO}_2} t 0.115 \Delta T = 1102 \times 1 \times 0.115 (512 - 100) = 52.2 \text{ kJ/kg.}$$

Then the heat absorption energy of 1 kg of Kovdor concentrate will be equal to:

$$\theta = \theta_x + \theta_c + \theta_w + \theta_v + \theta_{\text{a.c.}} = 933.2 \text{ kJ/kg.}$$

The resulting value corresponds to pure vermiculite concentrate, but it contains up to 10 wt-% of inert material, which also absorbs heat: $\theta_i = 0.1 c_i m \Delta T = 0.1 \times 942.5 \times (512 - 100) = 38.8 \text{ kJ/kg}$, where 0.1 is the mass content of inert material in 1 kg of concentrate; c_i is the heat capacity of the inert material (for sand at $20 - 600^\circ\text{C}$, c_i is on average $942.5 \text{ J/(kg}\cdot^\circ\text{C)}$ [7]); m is the mass of the initial concentrate (1 kg); ΔT is the temperature change during heating, $^\circ\text{C}$.

Without taking into account the inert material, the value θ for the pure vermiculite will decrease:

$$\theta = 0.9\theta = 0.9 \times 933.2 = 840.0 \text{ kJ/kg.} \quad (2)$$

The power of thermal radiation absorbed by vermiculite Q_T , W , taking into account the absorbing capacity of its grains ($\alpha_v = 0.768$ [9]), and the total specific heat absorption energy θ , W at a grain heating temperature of 512°C are related by the equation

$$\theta \Pi_G = Q_T, \quad (3)$$

where Π_G is the weight performance of the furnace, kg/sec .

The power Q_T is expressed by the formula [16]:

$$Q_T = 2\sigma T_e^4 f_e \varepsilon_e (1 + \alpha_v \varphi_{12}) \frac{1}{3} (2\varphi_1 + \varphi_2), \quad (4)$$

where σ is the Stefan-Boltzmann constant, $\sigma = 5.67 \times 10^{-8} \text{ W/(m}^2\cdot\text{K}^4)$ [14]; T_e is the temperature of the emitters surface

of the modules heating system, K ; f_e is the total surface area of all emitters of the furnace, m^2 ; ε_e is the nichrome emissivity factor (0.96 [17]); α_v is the absorbing capacity of the vermiculite mass; φ_{12} is the average angular coefficient for the resulting power flows of adjacent emitters (0.032 [16]); φ_1 and φ_2 are the average angular coefficients for the resulting power flows coming to a single vermiculite grain from adjacent emitters to the left and right [16].

Let us express performance by the relation

$$\Pi_G = m/t, \quad (5)$$

where m is the mass of vermiculite concentrate and foaming vermiculite, simultaneously located on the refractory surfaces of the modules of the two-module furnace (see Fig. 1b); t is the duration of vermiculite movement in the furnace, equal to the firing duration.

Equating Eqs. (3) and (4) and taking into account m/t , one can obtain

$$\theta \frac{m}{t} = 2\sigma T_e^4 f_e \varepsilon_e (1 + \alpha_v \varphi_{12}) \frac{1}{3} (2\varphi_1 + \varphi_2). \quad (6)$$

In the author's previous study [18], the formula for determining the mass of vermiculite, simultaneously located on the refractory surface of one module, was written in the form

$$m = \frac{\pi B D (l + \zeta)}{12(1 - k_p) k_f}, \quad (7)$$

but in this case (see Fig. 1b) for a furnace with two series-connected firing modules, Eq. (7) takes the form

$$m = \frac{\pi B D 2l_0}{12(1 - k_p) k_f}, \quad (8)$$

where l_0 is the length of the module operating surface, including the pouring zone, m ; k_p is the coefficient of porosity of the foamed material (0.35); k_f is the coefficient of foaming, $k_f \sim 0.0085 \text{ m}^3/\text{kg}$ [19].

To calculate the volumetric performance of the furnace P_V , m^3/sec (see Fig. 1b), Eq. (5), taking into account Eq. (8), will have the form

$$\dot{V} = \frac{\pi B D l_0}{6(1 - k_p) t}. \quad (9)$$

By setting the dimensions of the new furnace module: $B = 0.95 \text{ m}$ and $l = 0.05 \text{ m}$, one can obtain the performance on the Kovdor concentrate KVK-2 ($D = 0.002 \text{ m}$), equal to $0.0009 \text{ m}^3/\text{s}$ or $3.24 \text{ m}^3/\text{h}$. It is approximately 2 times higher than that of the prototype furnace ($1.5 - 1.75 \text{ m}^3/\text{h}$ [7]).

Further, solving together Eq. (8) and Eq. (5), after the appropriate transformations, one can obtain the formula for de-

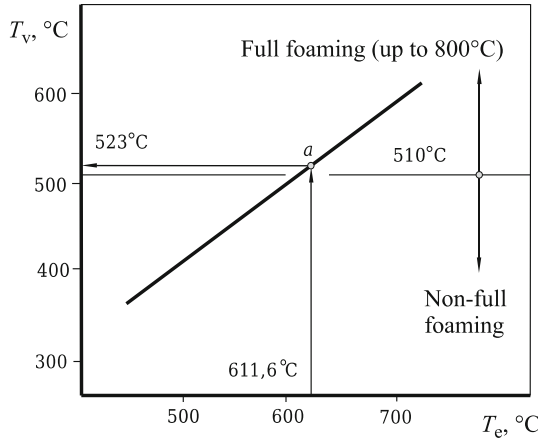


Fig. 6. Dependence of the temperature of Kovdor vermiculite on the temperature of the emitting elements of the furnace.

termining T_e , at which full vermiculite foaming will be ensured at a given performance:

$$T_e = \sqrt{\frac{\theta \pi B D L_0 \times 10^8}{4\sigma(1-k_p)F_e \varepsilon_e (1 + \alpha_v \psi_{12})(2\psi_1 + \psi_2)t}}. \quad (10)$$

The temperature will be calculated with the following initial data: the total energy of vermiculite heat absorption $\theta = 933200 \text{ J/kg}$, $B = 0.95 \text{ m}$, $a = 0.005$ and $b = 0.015 \text{ m}$ (see Fig. 2), $r = 0.035 \text{ m}$, $D = 0.004 \text{ m}$, $l_0 = 1.05 \text{ m}$, there are 10 emitters with a diameter of 0.005 m in one module, their length is $l_e = 0.95 \text{ m}$, $\varphi_{12} = 0.032$, $\varphi_1 = 0.058$ and $\varphi_2 = 0.033$. Angular coefficients are calculated using the algorithm described in article [16]. During firing time $t = 1.82 \text{ sec}$, vermiculite should foam at a temperature of 884.6 K or 611.6°C .

Let us use the formula for the relationship between the vermiculite temperature at the furnace output and the temperature of the emitters given in the article [16]:

$$T_v = T_e \sqrt[4]{\frac{f_e}{f_v} \alpha_v \varepsilon_e (1 + \rho_e \psi_{12}) \frac{2}{3} (2\psi_1 + \psi_2)}. \quad (11)$$

According to Eq. (11), a graph is constructed to establish the dependence of T_v on T_e , which in our case has the form shown in Fig. 6. It has been experimentally proven [20] that at a vermiculite temperature of $510 - 512^\circ\text{C}$, regardless of the size of its grains, if the foaming process had the character of a thermal shock of $1.5 - 3 \text{ sec}$, the vermiculite fully foams and reaches the minimum possible density. During the firing time of 1.82 sec in the new design two-module pouring furnace, the Kovdor vermiculite will be fully foamed, even before reaching the “zero” module. And it means that the temperature of the emitters, and, consequently, the consumed electric power can be slightly reduced in order to transfer the additional foaming of vermiculite to additional module 7 (see Fig. 1b). In order to do that, a thyristor power regulator

should be used when adjusting the furnace to the optimal operating mode.

Let us determine the specific energy intensity of Kovdor vermiculite firing based on the ratio of thermal and electrical powers N , W :

$$N = \sigma T_e^4 f_e = 3IU, \quad (12)$$

where k is a correction factor that takes into account the loss of electrical power of a three-phase circuit ($3IU$) when it is converted to thermal one.

The specific energy intensity of the firing process e_s , J/m^3 , taking into account Eq. (9), will be equal to

$$e_s = \frac{\sigma T_e^4 f_e}{\Pi_V} k. \quad (13)$$

With a loss coefficient k equal to 1.16 , the calculation by Eq. (13) gives $e_s = 50.4 \text{ J/m}^3$.

The possibilities and prospects of using electric modular-pouring furnaces with series-parallel connection of firing modules and a new design of the upper heating system were investigated. As a result a four-module furnace with a performance of $2.56 \text{ m}^3/\text{h}$ and a specific energy intensity of Kovdor concentrate firing of 63.5 MJ/m^3 was proposed [20]. These are very good indicators, practically equal to those of electric furnaces with a movable hearth platform [6]. However, due to the two upper parallel operating modules, in which vermiculite moves in a single-layer flow, its performance is lower than that of the new two-module furnace (2.56 versus $3.24 \text{ m}^3/\text{h}$), and the specific energy intensity is higher (63.5 versus 50.4 J/m^3). One should note that the experimental-industrial three-module prototype furnace has a specific energy intensity of at least 240 MJ/m^3 [3, 22].

CONCLUSION

The result obtained, i.e. a decrease in the specific energy intensity of the vermiculite firing process in a two-module furnace with a “zero” (non-electrified) module to the level of 50.4 J/m^3 , is a new radical technical solution in the development of the concept of electric modular-pouring furnaces. With smaller overall dimensions and less complex design, a furnace with a doubled performance with reduced power consumption by a third was developed. Such furnaces will compete with furnaces based on movable hearth platforms [6]. In comparison with them, two-module pouring furnaces have only one drive for the operation of a drum batcher, while furnaces with hearth platforms require an additional controlled drive to create an oscillatory motion of the moving hearth and the movement of vermiculite due to the effect of vibration transport.

The creation of the furnace heating system from a set of wire emitters of thermal energy with their upper location and fastening under the modules thermal covers is not only ener-

getically more efficient than the previous heating system of U-shaped chambers made of strip nichrome [7], but also provides the furnace throughput by doubling concentrate supply into the furnace and its performance.

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