

# *Simulation of the Process of Heat Treatment of Vermiculite Concentrates in Power Process Units with a Mechanical Base*

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**Abstract** — The article reviews the simulation of functional dependence of the heat treatment process time of vermiculite concentrates on their size groups (fractions) in power process units with a mechanical base plate, in which the movement of expanded vermiculite is set by vibro-transporting bulk material in the thermal field of electric heaters. At present we research the process of conductive layer-by-layer heat transfer into the vermiculite grains with the purpose to figure out the so-called “expected time” of temperatures balancing and the time of full expansion in the process of heat treatment of concentrates. The experimental data on the firing time of vermiculite concentrates from various deposits and their comparison with the results of analytical simulation are presented. It was firstly found that grain size of vermiculite concentrates depends on the duration of firing. This dependence was proved by the experimental results of the research.

**Keywords** — *vermiculite, firing time, levelling time, layer thermal diffusivity, conductive heat transfer*

## I. INTRODUCTION

A study of a number of domestic and foreign sources of information did not show any dependencies or recommendations on the duration of heat treatment of

vermiculite concentrates, with the exception of few not systematized data [1–14], obtained experimentally and from production experience.

The author of the present article has conducted an analytical study of the thermal diffusivity of vermiculite particles and the available empirical data and basing of the study results he conducted the simulation process of the heat treatment process of vermiculite concentrates of various fractions in power process units with a mechanical base plate.

## II. ASSUMPTIONS FOR SIMULATION PROCESS

The vermiculite concentrates from different manufacturers are not granulometrically unified due to the technology of enrichment of vermiculite ores and the concentrates fractionation processes. Figure 1 shows the distribution curve of the particles sizes of the concentrate of the fourth size group KVK-4 of the Kovdorsky field. The curve was constructed on the base of a histogram of residues on standard sieves in percent by weight. Sieve analysis of other size groups of concentrates gives similar results.

Obviously, if there are grains with nominal diameters  $d_n=1...7$  mm or more in the concentrate array, then the

duration of their heat treatment  $t_f$  will be greatly different. But it is possible to reduce the range of values of  $t_f$  by applying the narrow-band fractionation technology. But this is an irrelevant question. Here the problem of heat treatment simulation process of vermiculite concentrates is solved.

It is possible to understand how heat is transferred from flat grains of the concentrate to the depth of vermiculite grains that have begun to expand due to the consideration of these bulk grains as a layered structure and change of this structure at the heat treatment stages.

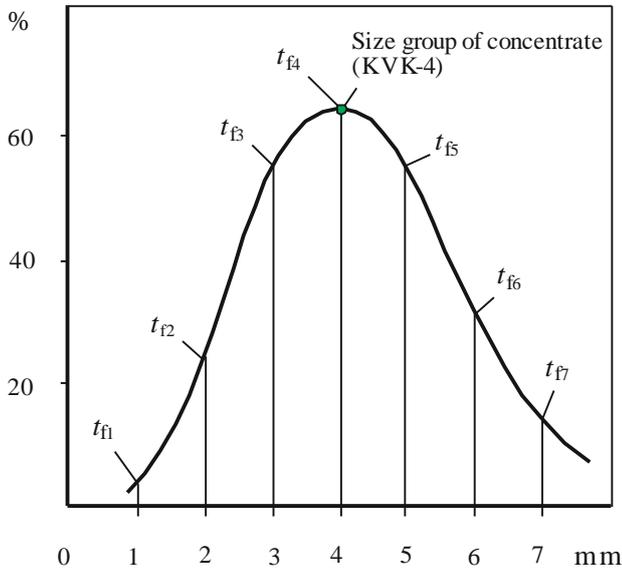


Fig. 1. The curve of vermiculite concentrate grain size distribution

Figure 2 shows the stages of transformation of vermiculite from the original flat particles (a) to fully expanded vermiculite (b).

First, the surface layers of vermiculite particles expand. They become the end parts of future grains mass, but as soon as they expand to 0.3...0.4 mm (for the time  $t_0$ ), they thermally insulate themselves and the penetration of thermal radiation from heaters into the deep layers stops.

This is the first assumption.

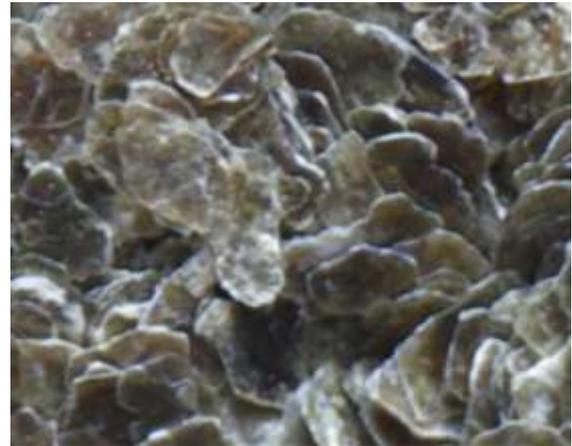
During the same time  $t_0$ , the grains partially open, thermal energy begins to penetrate into the depths of the still not expanded grains, but this is mostly due to conductive transfer from edges to center and temperature equalization.

This is the second assumption.

Let us make a few more assumptions for the study of the layer thermal diffusivity of mica:

- the peripheral temperature of the vermiculite grain is 600 °C, it is originated during the time  $t_0$  and it is maintained constant for the remaining time ( $t_f - t_0$ );
- the time during which the temperature in the center of the plate will reach 512 °C [16] corresponds to a fully expanded material and is the minimum sufficient firing time:  $t_f = t_0 + \tau$ ;

- there are the same processes in the near layers and there is no heat conducted between them;
- each layer (scale) has the property of denseness continuity, i.e., all properties are the same through the mass and surface;
- all the plates in the center and on the periphery have a temperature of preliminary heat treatment of 100 °C [15].



a



b

Fig. 2. Original concentrate (a) and finally expanded vermiculite (b)

### III. THE STUDY OF LAYER-BY-LAYER THERMAL DIFFUSIVITY

A model of thermal diffusivity of vermiculite flakes was considered during the research of the process of converting the exergy of vermiculite into its mechanical transformation in “zero” modular blocks of electric modular trigger furnaces [17].

But the problem of establishing the functional dependence of the heat treatment time of vermiculite concentrates on their size groups in this research was not solved.

Let’s consider a rectangular strip extracted from vermiculite grain with dimensions of  $a$  and  $b$  (Fig. 3, a). It is obvious that conductive heat transfer and temperature equalization will go in the transverse direction, since  $b < a$ , and longitudinal transfer will not affect the time equalization  $\tau$  at all.

Let us turn to the square plate (Fig. 3, b).

Obviously, in the white square fragment highlighted on the plate, the temperature will rise faster from the conductive heat flow coming from above, rather than from left and right flow. But if the process of complete temperature equalization was considered, the temperature in the white fragment would not reach 600 °C until its white round fragment in the center heated to 600 °C. This is a property of non-equilibrium thermal processes [18].

This means that for complete temperatures equalization over the entire area, the conductive flows to the left and to the right (or flows from above and below) are sufficient. There is no synergistic effect occur.

It is possible to select a strip (shown in white) on a plate of expanding vermiculite grain with a nominal diameter  $d_n$  (Fig. 3, c) and calculate using it (Fig. 3, d) the equalization temperatures time in vermiculite grain as a whole.

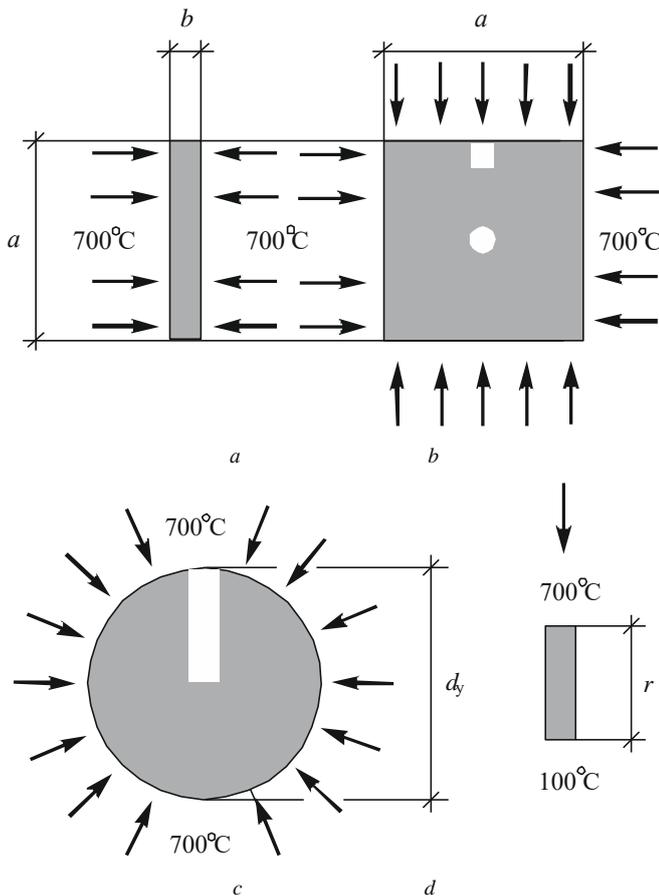


Fig. 3. To the visualization of the process of thermal diffusivity at layer-by-layer conductive heat transfer in expanding vermiculite grain

The ratio of the temperature difference  $\Delta T_{ef}$  on the periphery of the plate and in the center at the end of firing:

$$\Delta T_{ef} = T_1 - T_2 \tag{1}$$

to the temperature difference  $\Delta T_{bf}$  on the periphery of the plate and in the center at the beginning of firing

$$\Delta T_{bf} = T_3 - T_4 \tag{2}$$

gives the following equation [19]:

$$\frac{\Delta T_{ef}}{\Delta T_{bf}} = 1.03e^{-2.47 \frac{a\tau}{r^2}} \tag{3}$$

where  $T_1$  is the temperature at the periphery of the plate at the end of firing (600 °C),  $T_2$  is the temperature at its center at the end of firing 512 °C (incomplete temperature equalization),  $T_3$  is the temperature at the periphery at the beginning of the temperature equalization process for a time  $\tau = t_f - t_0$  (600 °C),  $T_4$  is the temperature in the center at the beginning of firing (100 °C),  $a$  is thermal diffusivity ( $m^2/s$ ),  $r$  is the dimensional parameter equal to the half the nominal diameter  $d_n$  of the original mica particle (m).

It has been established by the experimental means that for complete expanding of vermiculite in furnaces with a mechanical base plate, the final temperature should be approximately 505...520 °C [16].

Therefore, we take for further calculations the average value of  $T_2$  equal to 512 °C and we will consider the process of incomplete (but sufficient) equalization of temperatures during time  $\tau$ . The possibility of applying formula (1) is estimated by the expression [19]:

$$\frac{a \cdot \tau}{r^2} > 0.06, \tag{2}$$

where  $\tau$  is not known, but its expected value  $\tau_f$  can be calculated for the case when the temperatures at the ends of the selected strip (Fig. 3, d) do not affect the duration of their equalization [19]:

$$\tau_f = \frac{r^2}{a}. \tag{3}$$

Let's set the values of nominal diameters in the range of  $d_n$  and the corresponding sizes of the strip  $r$  (Tabl. 1, 2). Then let's determine the value of the coefficient of thermal diffusivity of a strip with the size  $r$  of vermiculite according to the equation [18]:

$$a = \frac{\lambda}{\rho \cdot c}, \tag{4}$$

where  $\lambda$  is the thermal conductivity coefficient of the vermiculite plate,  $\rho$  – is its true density, and  $c$  is the specific heat.

As it has been taken in the assumptions, each plate is characterized by a continuity of properties and the coefficient  $\lambda$  for them is approximately equal to the thermal conductivity of vermiculite coefficient and raw phlogopite in the direction of cleavage planes ~ 5.1 W/m·°C [21].

The density of hydromica is 2300 kg/m<sup>3</sup> [21], and taking into account the process of chemically bound water (approximately 18%) yield, it will be  $\rho$  1880 kg/m<sup>3</sup>. The heat capacity  $c$  of raw mica at 20 °C is 860 J/kg·°C [22].

By analogy with other minerals that are close in density in the temperature range of 500...800 °C, we take the value  $c$  with  $\sim 930$  J/kg·°C [22].

The calculation by expression (4) gives the value  $a=2.9 \cdot 10^{-6}$  m<sup>2</sup>/s.

According to the equation (3), we calculate the time  $\tau_f$  for all values of  $r$  and summarize in tables 1 and 2.

Check the condition (2), the values of the left part of the inequality are recorded in the table 1 and 2.

TABLE I. NOMINAL DIAMETERS, DIMENSIONAL PARAMETERS AND EXPECTED TIME

$d_n$ , mm	1.0	2.0	4.0	6.0	8.0	10.0
$r$ , mm	0.5	1.0	2.0	3.0	4.0	5.0
$\tau_f$ , s	0.0862	0.3440	1.3800	3.1030	5.5200	8.6200
$a\tau/r^2$	1.0000	0.9990	1.0500	0.9990	1.0005	0.9992

TABLE II. NOMINAL DIAMETERS, DIMENSIONAL PARAMETERS AND EXPECTED TIME

$d_n$ , mm	12.0	14.0	16.0	18.0	20.0
$r$ , mm	6.0	7.0	8.0	9.0	10.0
$\tau_f$ , s	12.4100	16.9000	22.0700	27.9300	34.4800
$a\tau/r^2$	0.99970	1.00020	1.00005	0.99900	0.99900

The obtained values show that condition (2) is fulfilled, since  $a\tau/r^2$  for all values of  $d_n$  of vermiculite concentrate is almost equal to one.

At these temperatures  $T_1 = 600$  °C,  $T_2 = 512$  °C,  $T_3 = 600$  °C and  $T_4 = 100$  °C the left side of equation (1) will be equal to 0.176. By successively transforming equation (1), we obtain:

$$\tau = 0.7158 \frac{r^2}{a} \tag{5}$$

To determine the time of incomplete (sufficient) temperature equalization in fully expanded grains obtained from particles of vermiculite concentrate with nominal diameters  $d_n$  from 1.0 to 20 mm, let's substitute the values of the dimensional parameter  $r$  from table 1, 2 and thermal conductivity coefficient  $a = 2.9 \cdot 10^{-6}$  m<sup>2</sup>/s into equation (7).

The results are summarized in table 3 and 4.

TABLE III. NOMINAL DIAMETERS AND EQUALIZATION TIME

$d_n$ , mm	1.0	2.0	4.0	6.0	8.0	10.0
$\tau$ , s	0.062	0.247	0.987	2.222	3.949	6.171
$t_f$ , s	0.0682	0.2720	1.0860	2.4440	4.3440	6.7880

TABLE IV. NOMINAL DIAMETERS AND EQUALIZATION TIME

$d_n$ , mm	12.0	14.0	16.0	18.0	20.0
$\tau$ , s	8.886	12.095	15.797	19.993	24.683
$t_f$ , s	9.775	13.305	17.377	21.992	27.151

The temperatures  $T_1$  and  $T_3$ , taken at 600 °C, are not taken randomly. In 2015, the experimental research of operation processes were conducted in a pilot electric modular trigger furnace with a so-called "zero" (non-electrified) module.

The temperatures were measured on the surface of the expanded grains obtained from the concentrate of the fourth dimensional group KVK-4. At the temperature of the heating elements of the furnace 720 °C and with high-quality expanding, the temperature of the expanded grains at the output was 587...612 °C with an average value of 599.5 °C.

#### IV. THE EXPERIMENTAL RESULTS

During the above-mentioned experiments on the basis of the expanding vermiculite flow, it was found that the approximate value of the "time of amplification"  $t_0$  is  $0.1 \cdot t_f$ , therefore the equation (7) with the substitution of the parameter  $d_n$  in it will take the final form and the estimated firing time will be:

$$t_f = 0.4 \frac{d_n^2}{a} \tag{5}$$

The analysis of the obtained data shows table 2 and 3, that the firing of large-sized concentrates without grinding particles and narrow-band fractionation is impractical, since an increase in the firing time of more than 6 seconds will lead to a decrease in furnace productivity. Therefore, figure 4 shows the dependence of the firing time on the nominal diameter of the concentrate particles with a size of up to 10 mm.

When  $d_n=4$  mm (the number 4 is the center of clustering for the KVK-4 concentrate, figure 1), the estimated firing time is 1.086 s (Fig. 4).

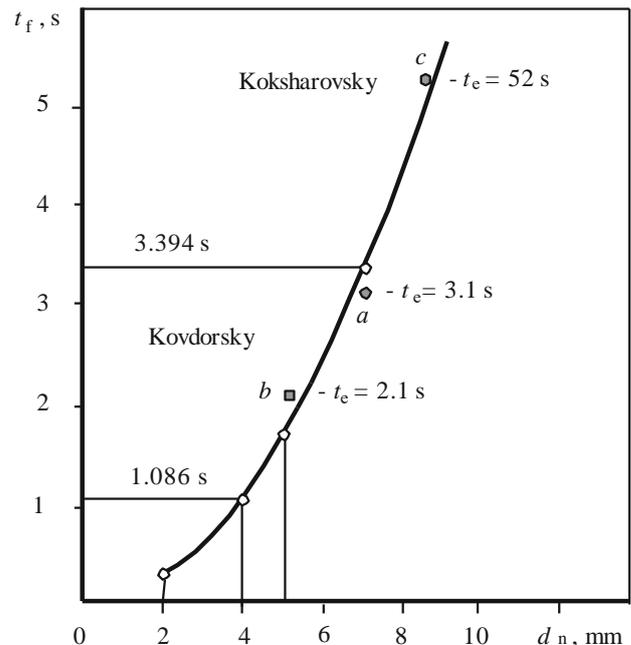


Fig. 4. The dependence of heat treatment duration on conditional diameter of concentrate particles

But particles of 7 mm or more in size are present in this concentrate, therefore, when setting up the furnace, the firing time is determined by the quality of expansion of the entire array: vermiculite should be the same as in figure 2, *b*. Therefore, the real time  $t_f$  when firing the KVK-4 concentrate should be 3.394 s (Fig. 4).

The experimental value of the firing time was 3.1 s, that is, point *a* in figure 4.

During this time in the furnace with a mechanical base plate when firing of this concentrate, the maximum performance is achieved with high-quality expanding. It can be said the same about the concentrate of the second dimensional group KVK-2: at  $d_n = 2$  mm,  $t_f = 0.272$  s (Tabl. 3, 4), but the actual estimated firing time, taking into account particles of 5 mm, should be 1.78.

The experimental value for setting up the furnace was 2.1 s, point *b*. in Fig. 4 (the experimental values were obtained when testing the prototype of the furnace considered in [16]).

One more experimental point can be added according to the results of setting up of the optimal firing mode for the KVK-4 concentrate of the Koksharovskiy deposit in the Primorsky Krai. In this concentrate, despite the 4th dimensional group, the size of the maximum particles reached 8.5...9 mm. The firing time of this concentrate was 5.2 s – point *c* in figure 4.

All experimental points coordinate with the calculated curve. As noted above, vermiculite concentrates firing without the processes of prior fractionation and grinding is impractical, but not only because of a decrease in productivity.

By setting up the furnace for a longer mode, the energy consumption is increased compared to fractional firing of pre-divided concentrates.

## V. CONCLUSION

The objective is achieved.

The authors built an analytical model of the heat treatment process for vermiculite concentrate on the base of the made assumptions. The previously unknown expression which determines the firing time, taking into account the “time of amplification”, as a function of the thermal conductivity coefficient of hydromica in the direction of the cleavage planes and the nominal particle diameter is obtained.

All the points which were obtained experimentally are coordinated with the constructed dependence; therefore the calculation formula can be considered satisfactory and used to calculate the firing time in electric furnaces with a mechanical base plate for all types and fractions of vermiculite.

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