DOI 10.1007/s11148-017-0047-6
Refractories and Industrial Ceramics *Vol. 58, No. 1, May, 2017*

HEAT ENGINEERING

ANALYTICAL MODEL OF ABSORPTION-REFLECTION PROPERTIES OF VERMICULITE UNDER THERMAL RADIATION CONDITIONS

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Translated from *Novye Ogneupory*, No. 1, pp. 15 – 20, January, 2017.

Original article submitted September 6, 2016.

A method for determining the absorption-reflection properties of a single grain of vermiculite and a dense single-layer array of intumescent vermiculite located on a planar surface under thermal radiation is considered. Based on the experimental graph of dehydration, the whole process of calcination and mechanical transformation of vermiculite can be broken down into stages. For each stage the averaged reflection and absorption coefficients are determined based on the idealized notion that the lateral faces of the grains due to the scaly structure completely absorb radiant energy of the heating elements, and the end faces completely reflect it. Based on the weighted average optical coefficients for a single grain and a single-layer array as a whole throughout the entire heat treatment period, a finite static optical model of the array was constructed.

Keywords: vermiculite, absorption-reflection properties, degree of blackness, static optical model of vermiculite flow.

INTRODUCTION

Most minerals are morphologically stable even under considerable heating: some physical properties change, but not the appearance. From this point of view, vermiculite is unique. Absorbing thermal energy at emitter temperatures of 500 – 800°C, it transforms not only in size and shape, but in structure and properties unlike any other mineral. Evidently, this transformation entails a significant change in optical properties: absorptivity (α), reflectivity (ρ), emissivity (ε) and transmittance (τ) both in the visible and infrared spectral regions. A review of more than two hundred vermiculite research related resources published between 2007 and 2016, aimed at finding the experimental values of α, ρ, ε and τ, did not yield conclusive results: no such data is available. Apparently, no experiments have been conducted in this area.

Thus, the question arises whether it is possible to conduct experiments to determine these optical characteristics directly. It should be noted that these values must be determined for a very narrow range of wavelengths of thermal radiation (0.78 – 40 μm) [1]. Therefore, the problem is rather complicated. It should also be noted that the process of complete transformation of vermiculite (from planar particles to expanded grains with a scaly structure many times larger than the original particles) in the above-mentioned temperature range lasts 1.8 – 4 sec [2, 3]. During this time all physical properties, including optical, change continuously and rapidly, so solving the problem becomes almost impossible. Of course, the optical properties of vermiculite in various deposits have been studied, but in these experiments absorption spectra were used to determine the chemical composition of the mineral [4, 5].

The aim of the present study is to obtain a static analytical model describing the absorption-reflection properties of a single-layer array of intumescent vermiculite under thermal radiation conditions. It is shown below that a simple statistical experiment is possible, and the results can be used to develop the desired analytical model.

MODEL OF THE OPTICAL PROPERTIES OF A SINGLE GRAIN

The process of mechanical transformation of planar particles into voluminous, expanded grains with a complex

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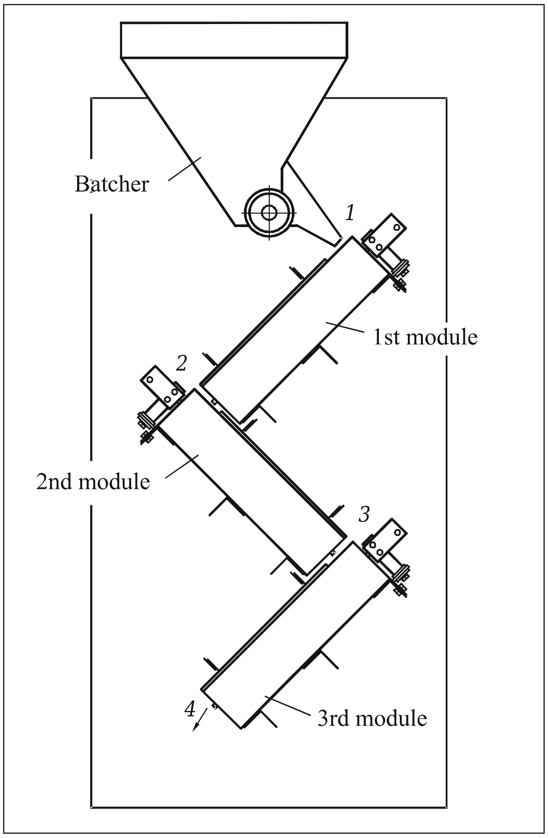

Fig. 1. Electric three-module furnace; the digits denote the areas of spillage.

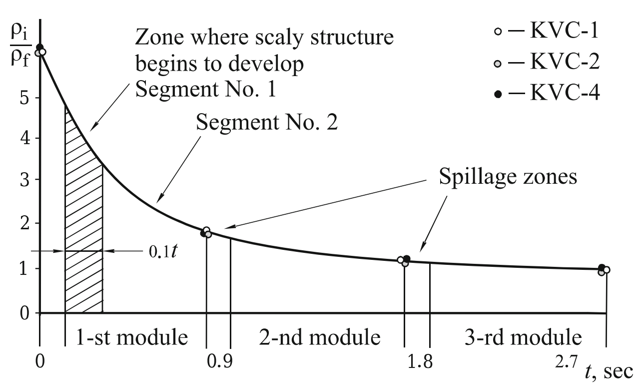

Fig. 2. Curve of dehydration of vermiculite from the Kovdorskoye deposit as it moves along the modules of the furnace.

scaly structure occurring in the thermal shock regime caused by the removal of chemically bound water (up to 20% of the initial mass of the mineral) can be approximately divided into stages. This requires an experimental vermiculite dehydration curve, which has been obtained many times not only experimentally, but also in production conditions on electric modular-pouring furnaces of various designs (Fig. 1) for different types of concentrates [6, 7]. Fig. 2 shows the graph of the change in the relative bulk density of vermiculite deter-

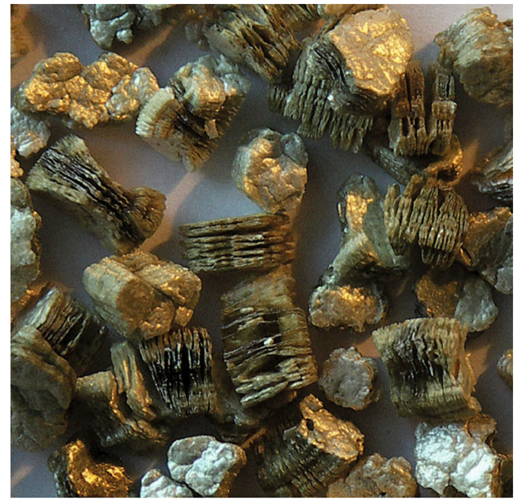

Fig. 3. Vermiculite sample collected in the spillage zone *2* (photograph fragment).

mined by the ratio $\rho_0 = \rho_i/\rho_f$ as a function of the transit time of the particles in the furnace modules t (ρ_i is the initial bulk density of the vermiculite concentrate, kg/m^3, ρ_f is the final bulk density of the expanded mineral, kg/m^3). The graphs are based on the results of measurements of ρ_i and ρ_f of vermiculite from the Kovdorskoye deposit of grades KVC-1, KVC-2 and KVC-3 (Kovdorsk vermiculite concentrate, the digit denotes the dimensions of the concentrate particles in mm [8]). For the concentrates of the Tatarskoye and Koksharovskoye deposits [9, 10] the dehydration curves are almost identical, so the dehydration curve can be considered universal [6].

From the change in the relative density ρ_0 (from 6 to 2) it can be concluded that vermiculite absorbs heat energy most intensively in the 1-st module. This is the first stage, and one more area of preheating can be distinguished in it. Visual observation through the open ends of the firing modules of the operating furnace shows that the travel time in this short segment is approximately 0.1t (t is the total vermiculite transit time in the furnace modules). Here, the vermiculite particles are generally still flat and have a maximum absorptivity. Mechanical transformation of particles and the development of a scaly structure begin after this segment. Thus, at the outlet from the first module when $\rho_0 \sim 2$ the samples collected from the zone of spillage *2* into the 2-nd module (see Fig. 1) show a pronounced scaly structure of the grains (Fig. 3). However, these grains are still short, and dark "cold" zones are clearly visible in the depths of the grains indicating that dehydration has not yet taken place. In the second stage, when ρ_0 changes from 2 to 1.15 structural formation processes slow down. Here the grains are partially expanded and insulate themselves. In addition, they have already accumulated a significant amount of absorbed heat, and the grains themselves not only absorb and reflect the radiant energy, but also emit it. The third stage is final; ρ_0 decreases by only 0.15 units, and vermiculite grains emerge from the third

Fig. 4. Fully expanded vermiculite (photograph fragment).

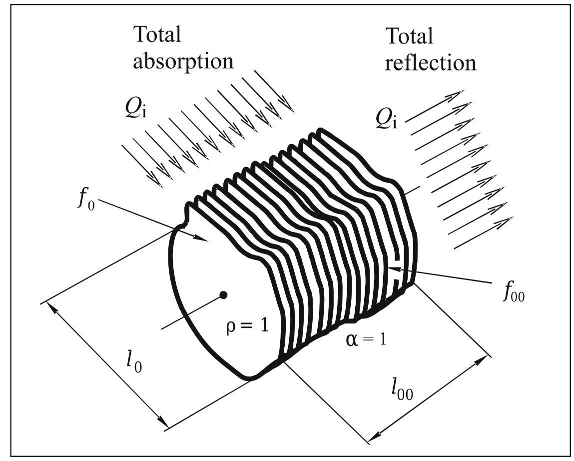

Fig. 5. Diagram for the model of absorption-reflection properties of vermiculite grains.

module completely expanded (Fig. 4). The ends of the grains correspond in shape to the original flat particles of the concentrate; they are golden in color and glisten well, indicating a very high reflectivity in the visible light range. The sides are pale yellow of a whitish shade and look dull. Their reflectivity is not so pronounced.

Consider the diagram of an expanded grain shown in Fig. 5. Idealizing the analytical model of absorption-reflection properties of the grain, the following assumptions can be made:

1. The dimensions of all single grains l_{00} and l_0 are equal.

2. The end faces f_0 in the movement segment before $0.1t$ in the first stage do not transmit or reflect the incident thermal radiation fluxes Q_i and have only absorption capacity ($\rho = 0$, $\alpha = 1$, $\tau = 0$).

3. The end faces f_0 in the second movement segment $> 0.1t$ in the first stage do not transmit or absorb the incident radiation fluxes Q_i and have only the capacity to reflect ($\rho = 1$, $\alpha = 0$, $\tau = 0$).

4. The lateral surfaces f_{00} in the motion segment $> 0.1t$ in the first stage and in the following two stages do not transmit or reflect the incident radiation fluxes Q_i and have only absorption capacity ($\rho = 0$, $\alpha = 1$, $\tau = 0$).

5. The values of the optical coefficients of a single grain under thermal radiation change in a stepwise manner in the segments of the first stage and from stage to stage.

Assumption 2 is based on especially high absorptivity in the thermal range, which is confirmed by a very rapid change in ρ_0 in segment No. 1 (see Fig. 2). Assumption 3 stems from the appearance of the grains: in the partially expanded state the end surfaces of grains are golden in color and very shiny indicating a very high reflectivity in the visible spectral range. Assumption 4 is based on the hypothesis that when radiant energy penetrates deep into the grain through thin cracks between the scales, it will be accumulated entirely by the grain in analogy with the black body model adopted in physics [11]. In the general form, the analytical model of optical characteristics of a single grain of vermiculite has the form

$$\alpha + \rho + \tau = 1.$$

Let us consider the change in optical coefficients by stages, considering that the first stage is divided into two segments.

The first stage, segment No. 1 ($0.1t$) (see Fig. 1). The particle is initially flat, the ratio of the dimensions is $l_{00}/l_0 \approx 0.1$. Absorption is complete ($\alpha = 1$), the model equation is

$$1 + 0 + 0 = 1. \quad (1)$$

The first stage, segment No. 2 up to the zone of spillage *2*. Samples from the 2nd zone of spillage (see Fig. 3) show that $l_{00}/l_0 \approx 1$. The average ratio of the dimensions in segment No. 2 is $l_{00}/l_0 \approx (0.1 + 1) = 0.55$, the ratio of surface areas is

$$\frac{f_{00}}{2f_0} = \frac{\pi l_0 \cdot 0.55 l_0}{2 \cdot 0.25 \pi l_0^2} = 1.1.$$

The ratio of areas is equal to the ratio of absorptivity to reflectivity, and their sum is unity. By solving the system of equations

$$\alpha/\rho = 1.1 \text{ and } \alpha + \rho = 1, \quad (2)$$

we find the equation of the model in segment No. 2 of the first stage:

$$0.524 + 0.476 + 0 = 1. \quad (3)$$

The second stage, the segment between the spillage zones *2* and *3*. The ratio of the dimensions at the transition to the second stage is $l_{00}/l_0 = 1$. At the end of the third stage this ratio reaches 1 – 3 (see Fig. 4) with an average value of 2.

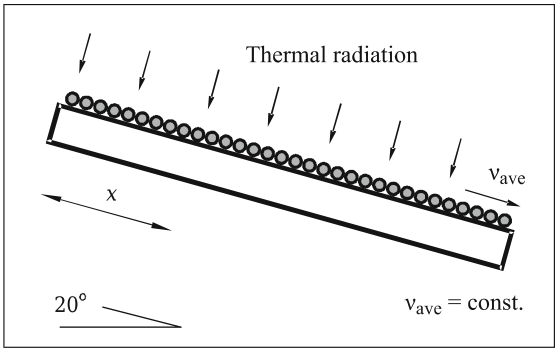

Fig. 6. Diagram of the vibrational movement of raw materials in a furnace with a moving hearth plate.

Then in the spillage zone *3* $l_{00}/l_0 = 1.5$, and the average ratio l_{00}/l_0 in the second stage will be equal to (1 + 1.5)/2 = 1.25. The ratio of areas is

$$\frac{f_{00}}{2f_0} = \frac{\pi l_0 \cdot 1.25 l_0}{2 \cdot 0.25\pi l_0^2} = 1.1.$$

Then the system of equations (2) changes:

$$\alpha/\rho = 2.5 \text{ and } \alpha + \rho = 1,$$

and the equation of the model in the second stage can be represented by the equality

$$0.714 + 0.286 + 0 = 1. \quad (4)$$

In the *third stage*, $l_{00}/l_0 = (1.5 + 2) = 1.75$, and the ratio of areas is

$$\frac{f_{00}}{2f_0} = \frac{\pi l_0 \cdot 1.75 l_0}{2 \cdot 0.25\pi l_0^2} = 1.1.$$

By analogy with the second stage, the equation of the model is represented by the sum

$$0.778 + 0.222 + 0 = 1. \quad (5)$$

Since the ultimate goal of the study is to formulate a static model of absorption-reflection properties of a single-layer array of vermiculite as a certain averaged constant, it is sufficient to find the weighted average of the absorption and reflection values over the entire time interval *t*:

$$\alpha_c = \frac{0.1 \cdot 1 + 0.8 \cdot 0.524 + 0.9 \cdot 0.714 + 0.9 \cdot 0.778}{0.1 + 0.8 + 0.9 + 0.9} = 0.69,$$

$$\rho_c = \frac{0.8 \cdot 0.476 + 0.9 \cdot 0.286 + 0.9 \cdot 0.222}{0.1 + 0.8 + 0.9 + 0.9} = 0.31.$$

In this case, the time interval *t* (the sum in the denominator) is 2.7 sec [12] for the three-module furnace for which vermiculite dehydration plots were obtained (see Fig. 2). The obtained analytical model of a single vermiculite grain is given by the equation

$$\alpha_c + \rho_c + \tau_c = 0.69 + 0.31 + 0 = 1, \quad (6)$$

which can be used for mathematical modeling of the processes of heat accumulation of vermiculite and heat transfer in the working chambers of the firing modules of modular-pouring electric furnaces [6], but already taking into account the reflectivity (previously the grain was treated as a black body). In such furnaces there is no continuous dense flow, the grains have accelerated movement due to gravity, moving away from each other and, possessing six degrees of freedom, are irradiated on all sides by heat energy.

When moving over the surface of a vibrating hearth plate of a furnace with an average speed v_{ave} (Fig. 6) and a certain ratio of the vibration parameters, plate incline, material size, batcher feed rate and temperature on the surface of the heating elements, the intumescent grains form a continuous, dense single-layer flow. A model of such a flow is significantly different from the single grain model.

Let us consider some results of observations and calculations.

EXPERIMENT

Proceeding from the assumptions that the lateral surfaces are absolutely black and the end surfaces completely reflect radiant energy, the experiment was to determine how, after exiting the lower module of the electric modular-pouring furnace, the grains would be distributed on a probe in the form of a flat surface oscillating in its own plane; how many grains would stand on end and how many would lie on their side. If all the grains lie on their sides then, in accordance with assumption 4 for the analytical model of a single grain, a single-layer array of intumescent vermiculite on the plate surface would have only absorptive capacity.

The first experiment was carried out on a sample of concentrate from the Koksharovskoye deposit. The sample belonged to the 4 mm size group and was tested on a modular-pouring furnace operating at the "Irkutsk Vermiculite" Company. The flat probe was located under the lower module in the spillage zone *4* (see Fig. 1) and moved slowly so that the falling grains packed on it in one layer practically without gaps between them. Then, using a thin-walled metal cylinder 52 mm in diameter, three fragments were extracted from the array and the number of grains lying on the side and standing on the end was determined by counting. The obtained results are shown in Table 1.

Absorptivity and reflectivity of a single-layer vermiculite array placed on a planar surface are determined by simple ratios:

$$\alpha_a = 370/(370 + 67) = 0.85,$$

$$\rho_a = 67/(370 + 67) = 0.15.$$

Calculations show that absorptivity of the array on a planar surface is 23.2% greater than absorptivity of a single grain simply due to the grain orientation to the position on the side. Although breakage of grains and a decrease in the dimension l_{00} occur due to movement in the furnace, the overwhelming majority of the grains in the array lie flat on their side.

The second experiment was carried out on the expanded vermiculite from the Koksharovskoye deposit belonging to the same size group. Fig. 7 shows a prototype of an electric furnace with a vibrating hearth plate without a heating system. Expanded vermiculite collected at the outlet of the modular-pouring furnace was supplied onto a spring-loaded plate excited by an eccentric actuator to oscillate in its own plane so that the vermiculite grains could slide on the surface but did not separate from it during movement. After stopping the plate, with the aide of a thin-walled metal cylinder, as in the first experiment, three fragments were isolated on the plate surface at random locations and the number of grains lying on their side and standing on their end was determined by counting. The obtained results are shown in Table 2.

In this case, absorptivity increased somewhat and reflectivity decreased, which apparently indicates the influence of oscillations, as a result of which some of the grains standing upright fell over:

$$\alpha_a = 408/(408 + 64) = 0.864,$$

$$\rho_a = 64/(408 + 64) = 0.136.$$

While in the first experiment the results were obtained for fully expanded grains, in this experiment in order to determine the averaged optical coefficients the distribution of the grains throughout the stages should be taken into account.

MODEL OF A SINGLE-LAYER ARRAY OF VERMICULITE

To model a dense single-layer array of vermiculite moving along the surface of a sloping furnace hearth plate, the following assumptions were made:

– the array has a regular structure of grain arrangement on the surface of the plate, where the space between the larger grains is filled with smaller grains;

– the regular structure of grains is not disturbed as they move;

– due to continuity of flow of intumescent grains, thermal radiation does not penetrate through the array and does not reach the surface of the plate;

– the heating of the plate is not ensured by the flow of radiant energy, but by the conductive transfer of heat from the heated vermiculite.

In segment No. 1 ($0.1t$) of the first stage, the flat vermiculite particles exhibit absolute absorptivity, $\alpha = 1$. In segment No. 2 of the first stage, because the ratio of dimensions is $l_{00}/l_0 \approx 1$, the probabilities of grains laying on the side and standing on their end are about equal, and the optical coefficients of the array are approximately equal to the absorptivity and reflectivity of a single grain: $\alpha = 0.524$ and $\rho = 0.476$.

In the second and third stages, l_{00}/l_0 are equal to 1.25 and 2, respectively, the probability of grains laying on the

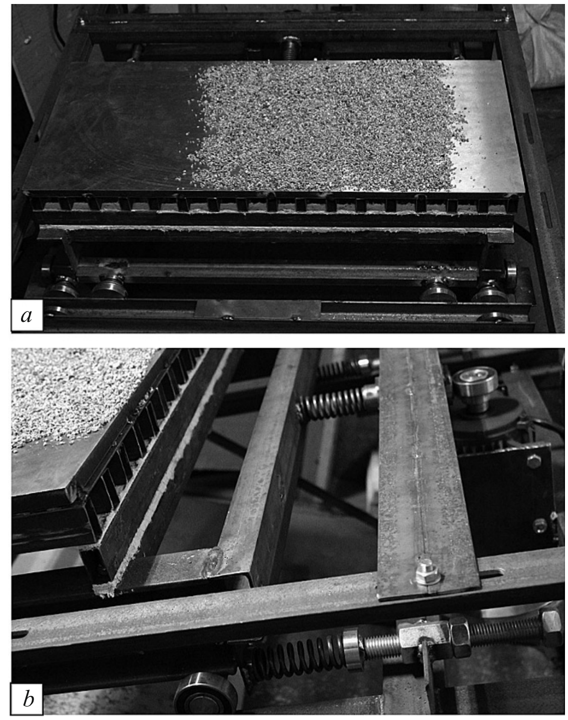

Fig. 7. Vibratory hearth plate of a furnace without an electric heating system (*a*, *b*).

TABLE 1. Results of the first experiment.

Trial number	Number of grains lying on the side	Number of grains standing up
1	115	31
2	122	17
3	133	19
Average value	370	67

TABLE 2. Results of the second experiment.

Trial number	Number of grains lying on the side	Number of grains standing up
1	121	24
2	150	32
3	137	8
Average value	408	64

side reaches a maximum, so a static analytical model of absorption-reflection properties of a single-layer array of vermiculite can be described by the coefficients α_a and ρ_a determined as weighted averages over the time interval *t*:

$$\alpha_c = \frac{0.1 \cdot 1 + 0.8 \cdot 0.524 + 0.9 \cdot 0.864 + 0.9 \cdot 0.864}{0.1 + 0.8 + 0.9 + 0.9} = 0.768,$$

$$\rho_c = \frac{0.8 \cdot 0.476 + 0.9 \cdot 0.136 + 0.9 \cdot 0.136}{0.1 + 0.8 + 0.9 + 0.9} = 0.232.$$

Here, absorptivity of the array compared to that of a single grain increases by 11.3%, which is also very important and should be taken into account in mathematical modeling of the processes of heat accumulation of vermiculite and heat transfer in the chambers of electric furnace modules with a vibrating hearth plate.

Thus, a static analytical model of a dense single-layer flow of vermiculite can be described by the equation

$$\alpha_a + \rho_a + \tau_a = 0.768 + 0.232 + 0 = 1. \quad (7)$$

CONCLUSION

The novelty of the study is in the obtained analytical model for a single vermiculite grain represented by the expression (6). The obtained result can be used to refine the earlier model of vermiculite flow (for electric modular-pouring furnaces) in the form of a continuous anisotropic body whose optical properties are expressed by the equation $\alpha^{xy} + \tau^{xy} = 1$ [6], in which only its absorptivity and transmittance along the *x* and *y* directions were taken into consideration. Even a simplified model that did not take into account reflectivity showed good agreement between the results of calculating the energy balance equations of the furnace-environment system (up to 15%) and the results of experiments [6].

Now this model can be represented in a new form: $\alpha^{xy} + \rho^{xy} + \tau^{xy} = 1$, which is another novel contribution of this work. Due to a more accurate description of optical properties, the accuracy of engineering calculations of electric modular-pouring furnaces is improved. But the main thing is that an analytical model of optical properties [equation (7)] of a single-layer dense flow of intumescent vermiculite on the vibrating hearth plate of a new concept furnace has been obtained. This concept can be used in mathematical modeling of heat generation and heat transfer in firing spaces of its modules. This is the third novel contribution of the completed research.

This research was supported by an FGBU grant from the "Fund for Promoting the Growth of Small Enterprises in the Scientific-Technical Sphere." Contract No. *1243 GS 1/21693.*

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