Using and assessing energy efficiency of electrical ovens with unit-type releasing intended for thermal energization of sungulite-vermiculite conglomerates

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Abstract. The paper deals with assessing energy efficiency of electric ovens supplied with unit-type releasing to be used in the thermal activation technology of vermiculite – phlogopite conglomerates. The analysis of a heat absorption process is given on the basis of the conglomerate particles moving in the conditions of heat radiation induced by an outer source and heat absorption taking place inside a special nonelectric unit on the account of inner energy accumulated by the particles.

1. Introduction
Technogeneous wastes of Kovdorski phlogopit-vermiculite deposit in Murmansk region hosts hundreds of thousands tons of vermiculite and sungulite [1] that are the raw material to produce thermal vermiculite and magnesian-silicate chemicals. Expanded vermiculite participates in soil-forming processes, whereas sungulite turns into an effective chemical after thermal energization that is able to reduce the mobility of heavy metals [2] and can be used in detoxification of technogeneously polluted soils and water objects.

The basic minerals in the parent raw material are (by mass) sungulite ~ 10%, vermiculite ~ 13%, pyroxene and olivine ~ 50 %, the remaining ones are antigorite, iron oxides and other minerals [1]. The technology of raw material dividing includes fragmentation, concentration in a hydro separator with the drain turnoff, drying followed by a magnetic separation and roasting [3]. The waste is composed of particles that are 0.1 to 0.2 mm in size and contains about 20% of vermiculite and ~ 14% of sungulite. After roasting it can be used as an ameliorant. The magnetic crop yield makes up more than 53 %. The nonmagnetic crop is the bearer of target products: vermiculite is represented by leaves up to 5 mm thick in the amount of ~ 37%, the amount of sungulite is ~ 25 %, and that of olivine-pyroxene rock makes up ~ 40 %. The yield of nonmagnetic crop is 13 % [3].

2. Experimental
The sungulite bulk density is ~ 1026 kg/m³. It is 21% lighter than that of olivine-pyroxene phase. So, it is not difficult to release vermiculite and sungulite by means of vibratory segregation.

It is evident that the faster is the heat rise, the higher is the degree of sungulite activation [2]. A thermal shock and holding at the temperature of 600 °C for 20 minutes are the optimum conditions.


Energy-saving electrical ovens with unit-type releasing supplied with heat energy recuperators [4] can be used to realize a thermal shock (200...240 °C/c).

The oven contains a raw material dosimeter 1 with a bin2, a roller 3, and a trough 4 (Figure 1). Electrical modules 5 supplied with recuperators 6 are joined to the heat chambers of an electrical unit 8 which has a Г-shaped form by a piping system 7. Modules 5 are covered with lids 9 and electric heaters attached to conducting heads 10 are placed under the lids.

![Figure 1. The lay out of an oven with a Г-shaped module](image1)

![Figure 2. A I-I cross section of a Г-shaped module](image2)

There are thermally insulated pockets 2 between the heat chambers 1 (figure 2) and they are separated by a roasting space 3. Hot air is vented into the chambers 1 through a piping system 7 (figure 1), whereas it is vented out with a vent exhauster through their lower holes. In their movement through the modules the conglomerate particles find themselves in the conditions of heat radiation. Some part of the radiant energy heats the air which is being released from the modules 5 (figure 1), whereas the other part of it together with its reflected flows is released through the cross-cut ends. The recuperators “collect” it from branch pipes and collectors to send it to a nonelectrical unit 8 as hot air ~380°C.

3. Result and discussion

The analysis of a vermiculite roasting process is given consideration to in paper [5]: the energy of its heat absorption, \( Q_{\Sigma} \), makes up 1202 kJ/kg.

Redistribution of the energy takes place while a conglomerate is being roasted:

\[
Q'_{\Sigma} = k_v \left( Q_1 + Q_2 + Q_3 + Q_4 + Q_5 \right) + \left( 1 - k_v \right) \times \left( Q_6 + Q_7 \right)
\]

(1)

where \( Q'_{\Sigma} \) is a complete conglomerate heat absorption energy, \( k_v \) is the index of a vermiculite portion by weight, \( Q_1 \) is the energy of hydrated water dehydratation, \( Q_2 \) is the heat energy of a “dry” mineral, \( Q_3 \) and \( Q_4 \) are the heat energy of change in phase and the superheating of water evaporations, \( Q_5 \) is the
heat energy of adsorbed gases heating, \( Q_6 \) is sungulite heating and \( Q_7 \) is the heat energy produced by evaporation of physical water adsorbed by sungulite:

\[
Q_6 = 0.955 \, c_1 \, m \, T \quad \text{and} \quad Q_7 = 0.045 \, c_2 \, m
\]

where 0.955 and 0.045 are the portions of the dry part and moisture by weight in 1 kg of sungulite, \( c_1 \) is an average sungulite specific heat capacity in the range of 20 \( \ldots \) 700 \(^\circ\)C (an average value of \( c_1 \) is \( \sim 943 \, \text{J/kg} \, \text{°C} \) [6]), \( m \) is sungulite mass (1 kg), \( T \) is the temperature of heating, \( c_2 \) is the specific heat of steam production (\( c_2 = 2250 \times 10^3 \, \text{J/kg} \)) [7].

The amount of heat energy received by “dry” sungulite while being roasted is:

\[
Q_6 = 0.955 \times 943 \times 1 \times 650 = 585.4 \, \text{kJ}
\]

where 650 \(^\circ\)C is the difference of roasting (750 \(^\circ\)C) and conglomerate preheating (100 \(^\circ\)C) temperatures before the roasting.

The heat energy of adsorbed water in the condition of change in phase is:

\[
Q_7 = 0.045 \times 2250 \times 10^3 \times 1 = 101.3 \, \text{kJ}
\]

The data obtained being taken into consideration, equation 1 is transformed into:

\[
Q = 1202 \times k_v + 686.7 \times (1 - k_v)
\]

The index of \( k_v \) changes within the limits of 0.35 \( \ldots \) 0.4, so the available energies relation of \( Q_\Sigma \) and \( Q_\Sigma' \) is dependent on vermiculite contents by weight. In equation (1), two members are used to show the accumulated heat: \( Q_\Sigma \) in the expanded vermiculite and \( Q_6 \) in sungulite. The heat energy of \( Q_\Sigma \) in 1 kg concentrate makes up \( \sim 560 \, \text{kJ} \) [4], whereas \( Q_6 \) makes up \( \sim 585 \, \text{kJ} \). \( k_v \), being equal, for example, to 0.4, the heat energy of \( Q_\Sigma \) accumulated by them is calculated as follows:

\[
0.4 \times 560 + 0.6 \times 585 = 224 + 351 = 575 \, \text{kJ/kg}
\]

This is the value of heat energy accumulated in the condition of a fully completed roasting process.

An intensive heat absorption is performed by conglomerate components in electrical modules due to radiant energy transference on vermiculite and sungulite particles. While expanding, vermiculite grains form a heating “jacket” which makes radiant energy penetration into deeper layers more difficult.

If we give consideration to the indices of sungulite thermometric conductivity, \( \chi_1 \), and expanded vermiculith one, \( \chi_2 \), [8] it is evident that

\[
\chi_1 / \chi_2 = \lambda_1 p_2 c_2 / \lambda_2 p_1 c_1
\]

where \( \lambda_1 \) and \( c_1 \) are the thermal conductivity (\( \sim 0.35 \, \text{W/m} \, \text{°C} \)) and specific heat capacity (\( \sim 800 \, \text{J/kg} \, \text{°C} \)) of sungulite, \( \lambda_2 \) and \( c_2 \) are the thermal conductivity (\( \sim 0.056 \, \text{W/m} \, \text{°C} \)) and specific heat capacity (\( \sim 1625 \, \text{J/kg} \, \text{°C} \)) of expanded vermiculite, \( p_2 \) is its density (\( \sim 200 \, \text{kg/m}^3 \)), \( p_1 \) is sungulite density (\( \sim 1000 \, \text{kg/m}^3 \)) [4]. The calculation performed in accordance with formula (3) results in the ratio of \( \chi_1 \) to \( \chi_2 \) as 2.4.

Sungulite gets heated faster, so the expansion of vermiculite is continued in a nonelectrical unit, the process being not caused by an outer source, as the hot air of heat chambers makes the heat leak from the roasting space smaller. In this case, we deal with the transport of radiant energy from sungulite to vermiculite grains and the conductive transport inside the grains from their outer layers to deeper ones. Besides, there is some heat exchange between vermiculite grains, too. Small grains that have already expanded are unable to absorb any energy but radiate and reflect it on greater neighboring grains instead.

Such is the model of heat absorption observed in vermiculite and sungulite conglomerates roasting.

\[
Q_\Sigma' = k_v (Q_3 + Q_4 + Q_5 + Q_2) + (1 - k_v)Q_6
\]
In this case, Q'_∪ is adopted heat, the process being not completed; k₁ is an index registering the portion of heat adopted by vermiculite before it enters the non-electric unit which is dependent on the temperature and time t of the conglomerate moving while being heated from an outer source and also on the components relation by weight. The index of k₁ is absent before the member of equation (4) which is (1 – k₁) Q₆ as sungulite had completely adopted the heat before it entered the non-electrical unit which is evident from equation (2). This fact accounts for the absence of Q₇ member in equations (3) and (4) as the water adsorbed by sungulite evaporated at the starting stage. In equation (4) the approximated equality shows that the thermal energy accumulated in the conglomerate can be lacking to complete the dehydration process This depends on k₁ and is expressed by the member of k₁k₁Q₂ + (1 – k₁) Q₆ of equation (4). Equation (4) can be balanced by changing t (the time of roasting) and the temperature in the oven, increasing the value of index k₁ and the time of a conglomerate movement through the non-electrical unit t₁ as well as its particle concentration in the working space. All these changes will make the losses resulting from heat transport from sungulite particles to vermiculite grains smaller.

The time of heat adoption grows by ~27 % on the account of the non-electric unit. This is why the temperature of heaters in the electric modules can be lowered. (Figure3) demonstrates the temperature and chrono interrelation for an oven with the regime point of a characterized by the parameters of T = 750°C and t₂ = 2.88 sec.

![Figure 3](image)

**Figure 3.** Chrono-thermal relationship

The oven is shifted into the temperature regime of T = 6270°C, point b, by increasing the roasting time in these limits and attaching the non-electrical unit. Using the interrelation between the parameters of a three-phase network, the area of heaters radiant surfaces, f, and the absolute temperature of T₄(°K) [4] we obtain the formula:

\[ 3 \times 1.27 \frac{I}{U} / f = \delta T^4 \]  

This way it is possible to determine the ratio of the oven unit current loading, I (A), in the regime points b and a basing on equation (5) and taking into consideration the area f quasi-increase by 27 %:

\[ I_a / I_a = 0.76 \]
where \( \sigma \) is a constant value by Stefan-Boltzmann (\( \sigma = 5.67 \times 10^{-8} \) W/m\(^2\)K) whereas \( U \) is a network line voltage (~220 W).

### 4. Conclusion

Thus, a non-electrical unit installing is to cause the reduction of energy consumption by 24%. This is an extreme prediction, but it allows to recommend the ovens under consideration as a means of realizing the technologies of minerals thermal activation.

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