Assessing energy efficiency of electric car bottom furnaces intended for thermal energization of minerals

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Abstract. The paper deals with a new concept of electric furnaces for roasting and thermal energization of vermiculite and other minerals with vibrational transportation of a single-layer mass under constant thermal field. The paper presents performance calculation and comparative assessment of energy data for furnaces of different modifications: flame and electric furnaces with three units, furnaces with six units and ones with series-parallel connection of units, and furnaces of new concept.

1. Introduction
In the course of upgrading of electric furnaces with unit-type releasing [1], several engineering solutions were applied that have changed their energy efficiency [2]. Creation of furnaces with series-parallel connection of units enabled the increase of the efficiency coefficient [2] while use of “zero” nonelectrical unit resulted in additional decrease of energy consumption. Thereby minimal specific energy intensity of roasting at the rate of 173–175 MJ/m³ was reached [1, 2], but it turned out to be not enough since the electricity cost is still high. In order ecological, fire-safe and explosion-proof electric furnaces find their level in industry, they should become competitive. Car bottom furnaces [3] are a decisive step to achieve the goal.

2. Experimental
Furnaces with unit-type releasing operate as gravity chutes: material motion occurs due to gravity forces, grains move with acceleration, and average interval δ between them increases: in the upper part of the unit δ = 0 while in the lower part δ = δ_max (figure 1). It is important to know how intervals δ will change. Table 1 shows the experimental values of vermiculite movement time along unit’s sections of 0.96 m long.

Table 1. Time of vermiculite movement along unit’s sections.

| Section # | Section 1 | Section 2 | Section 3 | Section 4 | Section 5 |
|-----------|-----------|-----------|-----------|-----------|-----------|
| Movement time t, sec | 0.37 | 0.17 | 0.13 | 0.1 | 0.09 |

It is obvious that grain concentration in the upper part of the unit is maximal; there are almost no hollow spaces between them (δ ≈ D) therefore the full power of incident heat radiation flux falls on work material. As the material moves, the time of sections’ passing declines, intervals grow, concentration decreases and becomes minimal in the lower part of the unit and average interval for vermiculite concentrate with weighted-mean grain diameter D becomes equal to δ = (6–6.5) D.
Relation of total area of grain projection on unit’s surface to the area of 0.2 m² occupied by them at the first section, by regular structure of a single-layer mass is 0.785. The same relation at the fifth section goes down to 0.046 and the concentration decreases by a factor of 17. Therefore only small part of radiant energy is absorbed by vermiculite here.

It is possible to drastically enhance heat transfer conditions by changing the way of material movement so that over the whole surface of the bottom the relation of total area of grain projection to the area of 0.2 m² at any section is maximum possible for the model of regular flow and makes up ~ 0.785. This could be reached by vibratory way of raw material feed, figure 2 (input and output heat fluxes are symbolically shown with arrows). By 15-20° inclination, granular material moves due to vibrations applied to the base. Asymmetric vibrations are particularly efficient since they cause one-way movement without inclination [4]. It is possible to organize such a movement on the account of installment of conical springs at the side where the flux should move to.

3. Result and discussion

Figure 3 demonstrates a single-phase block of a furnace with its own bottom. A complete furnace should contain three or six such blocks.

It consists of a frame 1, a bin 2, a drive 3 and a dosing drum 4 delivering raw material through a trough 5. The surface of a bottom 6 is produced from separate combined plates 7 made of heat-resistant steel to exclude its warping by heating. The plates are laid with an overlap to avoid retrograde movement of raw material. The bottom is installed on rollers 8 in frame guides. On the panel 9 there are heads 10 holding strip heaters 11 over the bottom surface with a clearance ranging from 0.002 up to 0.008 m. The bottom is covered with a removable heat-insulated lid 12 forming slit-like roasting space through which granular material moves forward for 2.5-5 seconds.

To deliver heat-treatable material, the bottom is secured by conical 13 and coil 14 springs. By rotation of a supplementary shaft with a bearing 15, a plunger 16 excites via a spring 17 asymmetric vibrations of the bottom inducing one-way movement of raw material. The whole block can be additionally inclined towards its movement.
The bottom makes resonance low-frequency vibrations (5…10 Hz) therefore it is possible to adjust the average speed of a single-layer mass movement on the account of the change of excitation frequency (vibration velocity control) and inclination angle.

Finished product is shot into a receiving bin (not depicted on the figure) through a trough 18.

Let us compare the capacities of a new furnace and of a pilot three-unit furnace with unit-type releasing [5] by vermiculite roasting. Its hourly expanded product capacity \( \Pi \) was \( \sim 1.75 \text{ m}^3 \) with roasting duration \( t \sim 2.84 \text{ sec} \) and unit dimensions as follows: \( B = 0.96 \text{ m (width)}, \ l = 0.89 \text{ m (length of a work section)}. \) In equivalent to expanded grains from all three furnace’s units, their total volume \( V_\Sigma \) was equal to:

\[
V_\Sigma = \Pi \times t \times (1 - k) / 3600, \tag{1}
\]

where \( k \) is the porosity index of expanded vermiculite mass (\( \sim 0.365 \)).

The total volume is \( 876600 \times 10^{-9} \text{ m}^3 \) while the volume of a single grain, expanded from the particle with an average nominal diameter \( D = 0.004 \text{ m}, \) equals \( 33.5 \times 10^{-9} \text{ m}^3 \).

The number of all grains in the furnace \( m \) equals \( 876600 \times 10^{-9} / 33.5 \times 10^{-9} = 26167 \) while the number of grains in one unit is \( m_1 = 26167 \div 3 = 8722 \). By regular structure of a single-layer mass on the bottom surface, the average interval between grains equals \( \delta = 0.0107 \text{ mm}, \) the clearance between them is \( \sim 0.0067 \text{ mm} \) whereas vermiculite concentration in the unit will be \( 8722 / (0.96 \times 0.89) = 10208 \) grains/m\(^2\).

In the new furnace vermiculite mass moves in such a way that the equality \( \delta \approx D \) is fulfilled and therefore grains occupy the whole surface of the bottom. With the same dimensions of the bottom \( (0.96 \times 0.89 \text{ m}), \) the number of grains along bottom width and length will be \( 0.96 \div 0.004 = 240 \) and \( 0.89 \div 0.004 = 222 \) respectively. The total number of grains will be \( 53280 \) pieces while vermiculite concentration on the bottom equals \( 53280 / (0.96 \times 0.89) = 62359 \) grains/m\(^2\) which is 6.1 times more.

Let the time of vermiculite stay on the bottom be \( t = 2.84 \text{ sec} \) by equivalent temperature conditions (on nichrome surface it is \( \sim 750^\circ \text{ C} \)). Vibrations of the bottom should secure average speed of expanding grains movement at the rate \( v = 0.31 \text{ m/sec} \). Based on the formula (1), it is possible to determine the unit’s production capacity per working hour, m\(^3\):
Hourly capacity of a three-phase furnace with three such blocks makes 10.65 m$^3$; it is 6 times as much as the capacity of a pilot unit-type furnace by equal electrical power consumption. Therefore specific energy intensity of vermiculite roasting will considerably decrease in the new car bottom furnace and be equal to $250.1 \times (1.75 / 10.65) = 41.1$ MJ/m$^3$ (compare to $\sim 250.1$ MJ/m$^3$ for the pilot furnace [5]).

Figure 4 demonstrates a strip diagram depicting change of specific energy intensity of various furnaces by vermiculite roasting: 1 – flame furnace, 3 – three-unit furnace, 3 – six-unit furnace with series-parallel connection of units, 4 – car bottom furnace.

Forecast of specific energy intensity of roasting in a three-block furnace of new concept is 41.1 MJ/m$^3$ which make only 14.4 % of energy intensity of one of the most advanced flame furnaces (286 MJ/m$^3$) working on hydrocarbon fuel [6].

4. Conclusion

Study of capacities of such energotechnological equipment for vermiculite roasting and thermal energization of other materials has been recently started. It is necessary to model the process of control of granular material movement on the furnace’s bottom, the processes of heat absorption and heat radiation transfer to working environment taking into consideration its optical properties, to determine energy relations by heat absorption of minerals under energization as well as to carry out the whole number of experimental investigations. But the forecast made encourages therefore a pilot sample of a car bottom furnace is being produced.

References

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