THERMAL AND ELECTRICAL CHARACTERISTICS OF A HIGH-FREQUENCY ELECTROTHERMAL FLUIDIZATION BED

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Based on an analysis of the thermal and the electrophysical characteristics of a fluidization bed with dielectric clay particles, a method has been developed of distending such particles by means of a high-frequency electric field for the production of ceramic sand.

The authors have studied the feasibility of applying heat from a high-frequency source to a fluidization bed with dielectric particles in a high-temperature distension process for the production of ceramic sand.

A peculiar feature of the process by which raw clay is transformed into a porous ceramic product (ceramic sand) is the concurrent effect of two factors: 1) a transition from the crystalline to the pyroplastic state at sufficiently high temperatures, and 2) a gas generating reaction in already hot grains of the material [1, 2]. These two factors are at the root of serious technological problems (adherence of distended particles to the hotter walls of the reactor, agglomeration with solid fuel particles passing into the bed, etc.) in connection with the supply of heat to a grain from the surrounding gases [3]. The quantity of heat which a grain receives is limited by the magnitude of the heat transfer coefficient α, while the temperature inside a grain drops from the periphery toward the center, i.e., in the direction opposite to the gas generating reaction.

In our proposed method of producing ceramic sand in a fluidization bed by means of a high-frequency electric field [4] there is heat generated within the volume of every ascending particle and the change in the direction of the temperature gradient is favorable to the gas generating reactions. Furthermore, it becomes possible to raise the temperature of particles sufficiently high to make the maximum rate of gas generation almost fall within the pyroplasticity range [5, 6]. In order to study and be able to control the technological processes of firing, the authors have thoroughly analyzed the thermal and the electrical characteristics of this system.

Temperature Characteristics. The temperature distribution inside a grain of radius R is described by the equation of heat conduction

$$c\gamma \frac{\partial T}{\partial \tau} = \frac{\lambda}{r} \frac{\partial^2 (rT)}{\partial r^2} + \dot{q} \tag{1}$$

with the boundary condition at r = R

$$-\lambda \left.\frac{\partial T}{\partial r}\right|_R = \alpha (T_s - T_0). \tag{2}$$

The rate of heat generation in the grain volume due to dielectric losses during high-frequency heating is

$$\dot{q} = 0.55\,\varepsilon' \,\mathrm{tg}\,\delta f E_{\text{м}}^2 . \tag{3}$$

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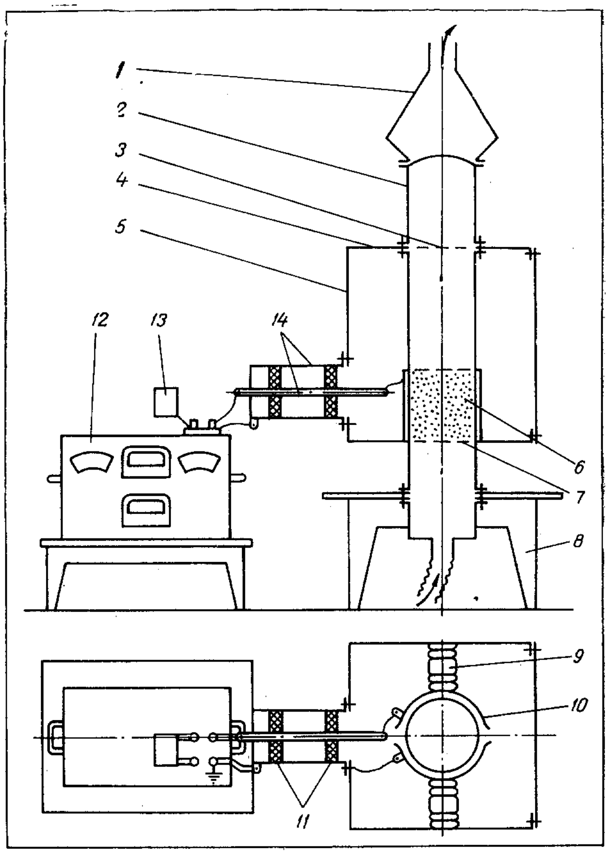

Fig. 1. Design of the test capacitor with shield and reactor, and spatial layout of the reactor and the Q-meter: 1) filter; 2) reactor made of acrylic glass; 3) metallic grid; 4) housing; 5) housing cover; 6) fluidization bed of granular dielectric material; 7) gas distributor grid; 8) stand; 9) insulators; 10) plates of the test capacitor; 11) insulating washers; 12) model E 9-5 Q-meter; 13) reference coil of the Q-meter; 14) coaxial leads.

During heating by a gas blast $\dot{q} = 0$, and during intensive endothermal distension processes it may even happen that $\dot{q} < 0$. Transient heating and cooling of a grain is characterized by two time parameters:

$$\tau_0 = \frac{R^2}{\lambda} c\gamma \quad \text{and} \quad \tau_a = \frac{R}{\alpha} c\gamma = \frac{2}{\mathrm{Nu}} \cdot \frac{R^2}{\lambda_G} c\gamma. \tag{4}$$

For argillaceous and ceramic sand particles with a radius R = 1-2 mm in a fluidization bed the values of these parameters are $\tau_0 \approx 0.1\text{-}0.2$ min and $\tau_S \approx 1\text{-}5$ min.

From the solution to Eqs. (1)-(2) with a constant adiabatic heating rate of a grain $\dot{T} = \dot{q}/c\gamma$, one can evaluate the temperature drop between center (r = 0) and surface (r = R) of a particle as well as between surface (r = R) and ambient medium:

$$\Delta T_c = T(r = 0) - T_s = \frac{1}{6} \dot{T} \tau_0 \quad \text{and} \quad \Delta T_s = T_s - T_0 = \frac{1}{3} \dot{T} \tau_a. \tag{5}$$

At an average rate of high-frequency heating $\dot{T} \approx 200$°C/min of particles with a radius R ≈ 1-2 mm, as had been attained by the authors, one could thus expect internal temperature drops $\Delta T_c \approx 5\text{-}10$°C and external temperature drops $\Delta T_S \approx 50\text{-}200$°C. External and internal temperature rises measured on individual grains with thermocouples have confirmed the validity of expression (5) as far as ΔT_c is concerned. Optical pyrometer measurements have shown that in a suspension of clay particles distended by a high-frequency field the temperature drops between grain surfaces and escaping gases do, indeed, reach ΔT_S 100-200°C levels.

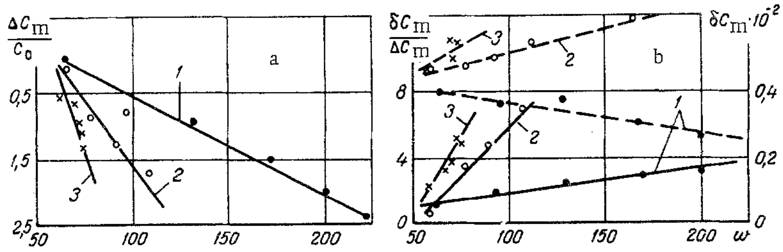

Fig. 2. Integral electrical characteristics of the fluidization bed as functions of the gas velocity (D = 70 mm, glass balls 0.6-1.2 mm in diameter): m = 0.25 (1), 0.5 (2), 0.75 (3). Solid lines indicate δC_m (pF), dashed lines indicate $\delta C_m/\Delta C_m$ (%). Gas velocity w (cm/sec), $\Delta C_m/C_0$ (%).

Integral Electrical Characteristics. The fundamental characteristic parameter of a conventional electrothermal fluidization bed with conducting particles is its total electrical resistance. In a dielectric fluidization bed, on the other hand, the rate of heat generation is determined by the tangent of the loss angle tan δ in expression (3). The bed itself, together with the inserted electrodes, constitutes an effective capacitor which is an inseparable part of the complete high-frequency generator. For this reason, the optimum performance of the electrical part of the apparatus is essentially determined by its integral characteristic parameters: its impedance and, above all, its total capacitance C. A change in capacitance C as a result of the bed expansion and of the continuous bed height fluctuations may, at a sufficiently large amplitude, disturb the stability of the high-frequency generator mode and reduce the amplitude of the electric field E_M inside the effective capacitor.

The effective capacitance includes the capacitance of the lower bed part filled with grains and the capacitance of the empty (gas-filled) upper part. As a stationary bed becomes fluidized, the height of the lower part increases while, at the same time, the effective dielectric permittivity ε' of the two-phase gas – solid random mixture filling the lower part decreases. The Odelevskii formula [7] for ε' of an expanding granular bed yields the change of mean capacitance $\Delta C_m = C_m - C_0$ during transition from a stationary loose to a fluidized bed. The fluctuations of the effective capacitance $\delta C = C - C_m$ in a fluidization bed could not be determined a priori and it has been necessary, therefore, to resort to an experiment.

The integral electrical characteristics (capacitance and quality factor) of a dielectric fluidization bed were measured on a cold model at an f = 20 MHz frequency with the aid of a special attachment to the model E 9-5 Q-meter for recording the values on a loop oscillograph. The layout of the test capacitor, the reactor, and the Q-meter is shown in Fig. 1.

The reactors were made of acrylic glass in the shape of cylinders with an inside diameter D = 70 mm and D = 140 mm. The gas distributor grid was made of glass fiber and felt. The dielectric particles were quartz sand 0.14-0.6 mm in diameter, glass balls 0.6-1.8 mm in diameter, and ceramic sand 2-5 mm in diameter.

The height of the test capacitor plates was in each case made equal to the reactor diameter (H = D). The relative heights of the stationary loose bed were m = 0.1D, 0.25D, 0.5D, and 0.75D respectively.

The velocity of the fluidizing gas was varied so as not to exceed a certain maximum w_{max} for a given bed at which still not a single particle would leave the measured bed volume, i.e., rise above the height of the test capacitor plates.

In this way, the quantity of solid phase within the measured volume remained constant throughout each test and equal to its mass in the original loose stationary state. The greater the initial fill m of the capacitor was, the lower was the maximum allowable velocity w_{max}.

The integral electrical characteristics for every hydraulic mode are random functions of time. Therefore, the oscillograms were evaluated by averaging the characteristics of such a random process over a sampling time of τ = 10 sec. The mean change in capacitance relative to a stationary bed $\Delta C_m = C_m - C_0$ and the mean fluctuation of capacitance δC_m (both absolute and relative values) as functions of the gas velocity w are shown in Fig. 2 for one of the test series.

A thorough analysis of the frequency characteristics has shown that fluctuation frequencies in the 1-6 Hz range are predominant here and that the mean fluctuation frequency in a fluidization bed is, quantitatively, a linear function of the bed height, as has been mentioned by the authors earlier in [8]. The

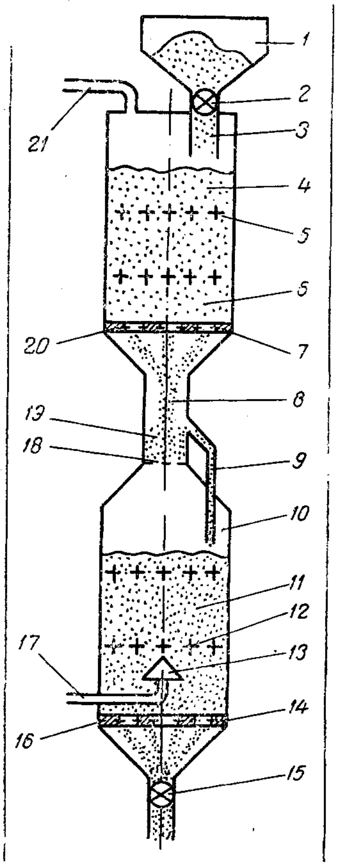

Fig. 3. Schematic diagram of a fluidization furnace with heat utilizing beds in motion: 1) bin with raw material; 2) charge feeder; 3) feed tube; 4) upper heat utilization zone; 5) leveling baffles; 6) upper raw-material moving bed; 7) upper support grid; 8) process zone; 9) overflow; 10) lower heat utilization zone; 11) lower final-product moving bed; 12) leveling baffles; 13) gas distributor grid; 14) lower support grid; 15) discharge feeder; 16) slide valve; 17) inlet tubing; 18) gas distributor grid; 19) fluidized bed; 20) slide valve; 21) outlet tubing.

following empirical relations between the frequency of capacitance fluctuations and the bed height have been derived from the test data:

$$
\begin{aligned}
f_m &= 0.25\sqrt{\frac{g}{h}} \quad \text{for the D = 140 mm reactor}\\
f_m &= 0.2\sqrt{\frac{g}{h}} - 1.9 \quad \text{for the D = 70 mm reactor}
\end{aligned}
\tag{6}
$$

Upon reexamination of the integral capacitance characteristics shown in Fig. 2, one notes the small relative variation. According to the formula derived by V. I. Odelevskii, the relative capacitance deviation $\Delta C_m/C_0$ during transition from a stationary to a fluidized bed (Fig. 2a) does not exceed a few percent under operating conditions. Under the given hydraulic conditions here (ΔC_m = const), however, the ratio $\delta C_m/\Delta C_m$ reaches 10% (Fig. 2b) but, when referred to the capacitance of the initial bed, $\delta C_m/C_m \approx \delta C_m/C_0$ amounts to a fraction of a percent and is thus of an order of magnitude smaller than the local density fluctuations [8].

This extremely low fluctuation frequency f of the effective capacitance, relative to the intrinsic generator frequency (f = 20 MHz), ensures a quasi-steady operation of the generator. The small amplitude of capacitance fluctuations ($\delta C_m/C_m < 0.2\%$) ensures practically stable energy characteristics of that generator.

Experimental Apparatus. The design of the experimental apparatus [9] was based on studies concerning the electrophysical properties of a dielectric fluidization bed and the temperature characteristics of the firing process. Consideration was given to the economics of utilizing the heat from solid products of firing and from gases escaping the reaction zone. During the continuous process, ceramic sand at a 1100-1300°C temperature is discharged on one side of the reactor and air at a 900-1100°C temperature is discharged on the other side. Furthermore, an examination of the electrophysical properties of raw clay has shown that the electrical parameters of the effective capacitor can be made stable by a preliminary heating of the particles and feeding them into the firing zone at an up to 600°C temperature.

All these considerations have led to the design of a trizonal firing furnace with a stepped-counterflow heat utilization system. The experimental apparatus shown schematically in Fig. 3 has a production capacity of 6-15 kg ceramic sand per hour. The high-frequency energy was supplied from a standard 10 kW oscillator operating at a 40.68 MHz frequency. The oscillator was loaded with a reactor 80 mm in diameter containing a fluidization bed with a 0.3-3.0 mm fraction of argillaceous particles.

Tests performed on this experimental apparatus have confirmed the theoretical conclusions concerning the temperature and the electrical characteristics of a dielectric fluidization bed, also the correctness of the engineering solutions to the technological problems. The operating mode fluctuated within a fraction of a percent in terms of amplitude and within a few cycles per second in frequency.

NOTATION

R, r	are the radius of a grain and the radius to any inside point;
$T(r)$	is the temperature inside a grain;
T_C	is the temperature at the grain center;
T_S	is the temperature at the grain surface;
T_0	is the ambient temperature;
τ	is the time coordinate;
τ_0	is the time of temperature leveling inside a grain;
τ_a	is the time of temperature leveling between grain and ambient medium;
λ	is the thermal conductivity of grain material;
$c\gamma$	is the specific heat in terms of volume of grain material;
λ_G	is the thermal conductivity of gas;
α	is the heat transfer coefficient;
$\dot{q}$	is the volume rate of heat generation;
ε'	is the dielectric permittivity of grain material;
f	is the frequency of high-frequency electric field;
E_M	is the amplitude of high-frequency electric field;
$\tan \delta$	is the loss tangent of grain material;
C	is the capacitance of effective capacitor with fluidized bed;
C_m	is the mean effective capacitance;
C_0	is the capacitance of effective capacitor with stationary bed;
D, H	are the diameter and height of reactor;
h	is the height of fluidized bed;
$m = h_0/H$	is the relative initial fill of a reactor;
w	is the linear velocity of gas stream.

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