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NUMERICAL SIMULATION OF PLASMA TREATMENT OF CHARGE USED IN VITRIFICATION OF RADIOACTIVE WASTES

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The process of plasma treatment of charge used in vitrification of radioactive wastes is simulated numerically. Optimum conditions providing heating of particles in the charge to vitrification temperatures are determined for a 200-kW reactor.

Vitrification of radioactive wastes using low-temperature plasma as a heat-transfer agent is advantageous over conventional methods in simplicity and compactness of the apparatus, high output, reliable remote control, and controllable amounts of effluent gases [1]. A broad variety of factors affecting the vitrification process hamper detailed investigation of various simultaneous interactions in the plasma flow-charge-reactor wall system. Therefore, it seems useful to combine experimental studies with less labor-consuming theoretical investigations.

In the present paper results of numerical calculations of motion and heat transfer of particles in the vitrifying charge in a flow of air plasma are presented. Composition of the charge used in calculations (8.66 mass % of CaO, 4.33 of B_2O_3, 2.24 of Fe_2O_3, 44.78 of SiO_2, and 40.11 mass % of $NaNO_3$) corresponds to the radioactive waste used in vitrification.

In the developed mathematical model of motion and heat transfer of vitrifying charge particles in the plasma flow in the channel of a direct-flow cylindrical vertical reactor it is assumed that temperature and velocity of the gas flow across the reactor cross-section are constant and equal to their mean-mass values, the gas pressure is constant, the particles are monodisperse and homogeneous in composition, there is no temperature gradient in the particles, the particle distribution over the cross-section of the reactor is uniform, radiative heat transfer from the plasma to the walls of the reactor and the particles as well as heat transfer from the particles is negligible, wall temperature is preset, the course of physicochemical transformations in the charge is only limited by heat transfer, and the composition of products corresponds to equilibrium and is determined by the temperature of the particles.

The basic equations of the mathematical model are as follows:

The equation of conservation of the number of particles in the disperse material

$$\frac{d}{dx}(v_p n_p) = 0, \tag{1}$$

The continuity equations of the condensed phase and gas

$$\frac{d}{dx}(v_p \rho_p) = n_p v_p \frac{dm_{pl}}{dx}, \tag{2}$$

$$\frac{d}{dx}(v_g \rho_g) = -n_p v_p \frac{dm_{pl}}{dx}, \tag{3}$$

The equation of motion of the particles

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$$v_p \frac{dv_p}{dx} = \frac{f}{m_{p1}} + g, \tag{4}$$

The equation of energy balance for the disperse material

$$v_p \rho_p \frac{dh_p}{dx} = nQ_{p1}, \tag{5}$$

The equation of energy balance for the plasma-forming gas

$$\frac{d}{dx}(v_g \rho_g h_g) = -\frac{dQ_w}{dx} - \frac{d}{dx}(v_p \rho_{pr} h_{pr}), \tag{6}$$

where dQ_w/dx is the heat flux from the gas into the wall of the channel per its unit length and the second term in the right-hand side characterizes the energy spent by the high-temperature gas in heating the charge, the products formed from the charge, and on concurrent physicochemical transformations.

In order to close system of Eq. (1)-(6), it should be supplemented with a number of relations, in particular, with expressions for the heat flux into a particle

$$Q_{p1} = \alpha S_{p1} (T_g - T_p), \tag{7}$$

the heat flux from the plasma to the wall in a section of dx in length

$$dQ_w = \mathrm{St}\,[h_g(T_g) - h_g(T_w)]\rho_g v_g \pi D dx, \tag{8}$$

the force exerted on a particle by the gas

$$f = C_D \rho_g \frac{\pi d_{p1}^2}{4} \frac{(v_g - v_p)\,|v_g - v_p|}{2}. \tag{9}$$

The air drag coefficient C_D is equal to $24/\mathrm{Re}_p$ at $\mathrm{Re}_p \le 2$ and $19/\mathrm{Re}_p$ at $\mathrm{Re}_p > 2$ [2].

In calculating the coefficient of intercomponent heat transfer $\alpha = \mathrm{Nu}\lambda_p(d_{p1}\overline{VB})$ and the Stanton number St we used the relations obtained in an experimental study of heat transfer in plasma treatment of phosphorite [2]. The following expression was suggested for the Nusselt number

$$\mathrm{Nu} = 2\frac{\lambda_g(T_p)}{\lambda_g(T_g)} + 0.78\,\mathrm{Re}_p^{0.5}\,\mathrm{Pr}\left(\frac{\rho_g(T_g)\mu_g(T_g)}{\rho_g(T_p)\mu_g(T_p)}\right)^{0.2}\varepsilon_1, \tag{10}$$

where β is the ratio of the volumes of the disperse material and gas and the correction term ε_1 is equal to 1 at $\beta \le 4\cdot10^{-4}$ and $7.82\cdot10^{-8}\beta^{-2.1}$ at $\beta > 4\cdot10^{-4}$.

The following relation was obtained for the Stanton number

$$\mathrm{St} = 0.364\,\mathrm{Re}_x^{-0.5}\,\mathrm{Pr}^{-0.67}\,\varepsilon_2\varepsilon_3, \tag{11}$$

where $\varepsilon_2 = 0.945(\beta\cdot10^4)^{-0.125}$ is a correction for the effect of concentration of the disperse material; $\varepsilon_3 = 1.87(x/D)^{0.238}$ is a correction for the conditions of formation of the flow; $\mathrm{Re}_x = \rho_g v_g x/\mu_g$ is the Reynolds number along the longitudinal coordinate; Pr is the Prandtl number.

The quantities dm_{p1}/dx and $d(v_p\rho_{pr}h_{pr})/dx$ in Eq. (2), (3), and (6) were determined from the results of special thermodynamic calculations of the equilibrium composition and enthalpy of the air-vitrifying charge system on the basis of the relations

$$m_{p1} = m_{p1}(T_p); \quad T_p = T_p(h_p); \quad h_{pr} = h_{pr}(T_p).$$

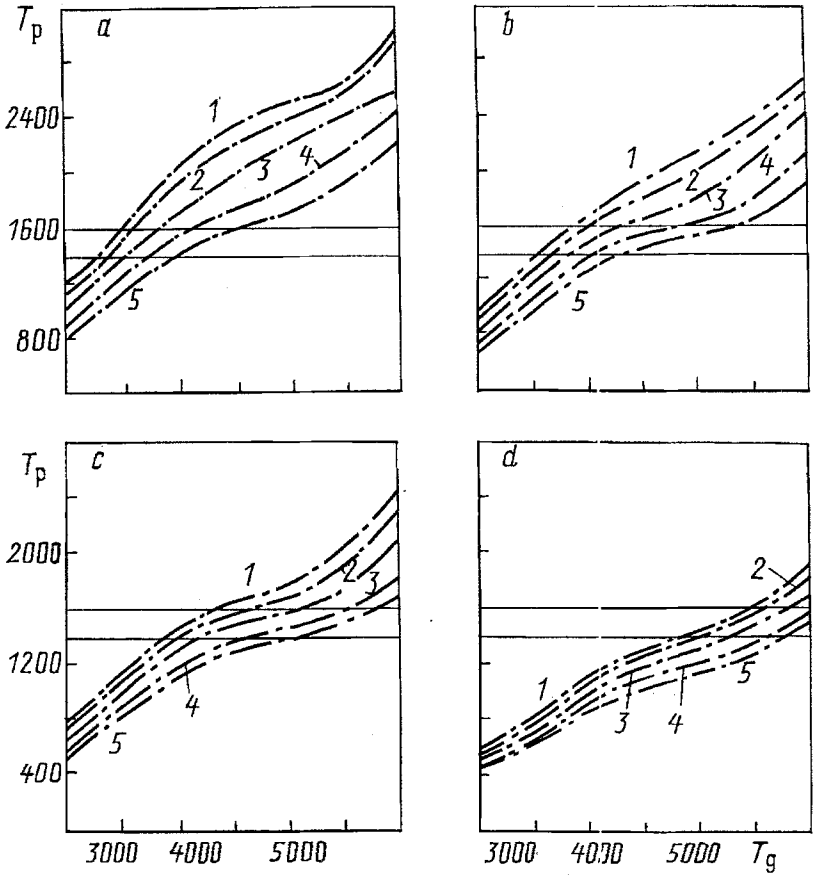

Fig. 1. Plot of maximum temperature of particle heating from initial plasma temperature at charge-gas mass ratio equal to 1 (a); 1.5 (b); 2 (c); 3 (d). Particle sizes are 25 (1); 50 (2); 100 (3); 200 (4), and 300 μm (5). T_p, T_g, K.

In order to close system of Eqs. (1)-(11), it was supplemented with the equations of state of a ideal gas, the condition of constant pressure of the gas, and expressions describing the effect of temperature on the thermophysical properties of the plasma-forming gas. The initial conditions for the system at $x = 0$ are as follows:

$$\rho_p v_p = \frac{4}{\pi D^2} G_p; \quad \rho_g v_g = \frac{4}{\pi D^2} G_g; \quad v_g = v_{g0}; \quad d_{p1} = d_{p0}; \quad T_g = T_{g0}; \quad T_p = T_{p0}.$$

Investigation of the process of plasma treatment of a vitrifying charge with the mathematical model adopted is reduced to solution of the Cauchy problem for a system of ordinary differential equations. The problem was solved numerically with Euler's method.

In the calculations the following basic data were used: diameter of the reactor channel, 5 cm; wall temperature of reactor, 500 K; initial velocity of the particles, 10 m/sec; and mass flow rate of gas, 7 g/sec. The charge-air mass ratio was 1, 1.5, 2.3. The intial temperature of the plasma was varied in the range of 3000 to 6000 K with a step of 500 K. The initial particle sizes were preset to be 25, 50, 75, 100, 150, 200, 250, and 300 μm.

Analysis of the calculation results has shown that if only the condition of attaining temperatures of 1400-1600 K necessary for virtification by the particles is assumed as a necessary condition, at a charge-gas mass ratio (G_p/G_g) of 1, it is sufficient that the initial temperature of plasma be 3250-4500 K; at $G_p/G_g = 1.5$, 3500-5500 K; at $G_p/G_g = 2$, 3800-5750 K; at $G_p/G_g = 3$, 4750-6000 K (Fig. 1). However, in view of the residence time of particles in the reactor, many of the conditions enumerated are unacceptable. If the length of the plasma reactor is limited to 1 m, while in choosing conditions providing heating of particles of various sizes to 1400 K, the data shown in Fig. 2 should be taken into consideration. It follows from these data that at $G_p/G_g = 3$, effective processing of 300 μm particles is impossible even at an initial temperature of 6000 K.

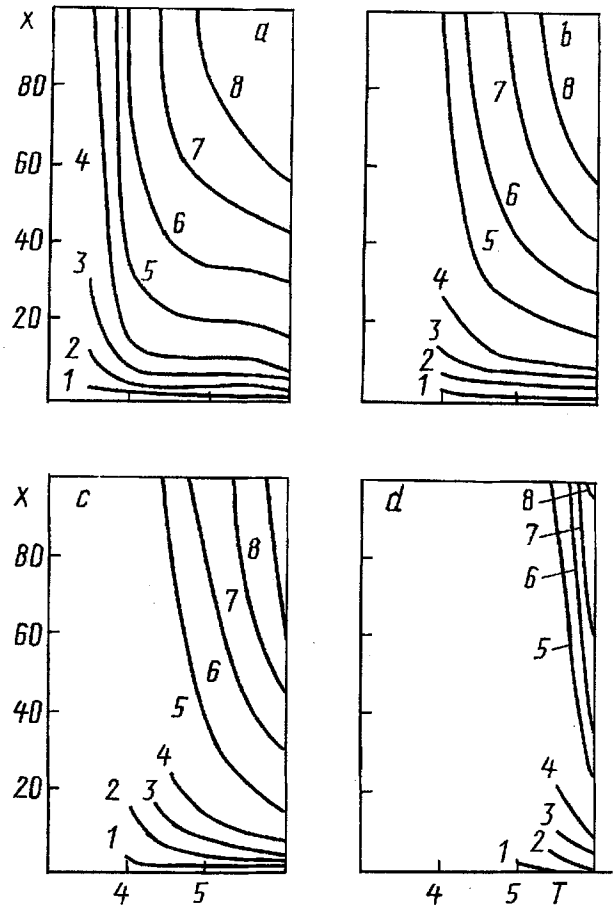

Fig. 2. Plot of the distance from the initial cross-section of reactor over which particles reach 1400 K versus initial plasma temperature. The charge-air mass ratio is 1 (a), 1.5 (b), 2 (c), and 3 (d). Particle size is 25 (1); 50 (2); 75 (3); 100 (4); 150 (5); 200 (6); 250 (7); and 300 μm. x, cm; T, K.

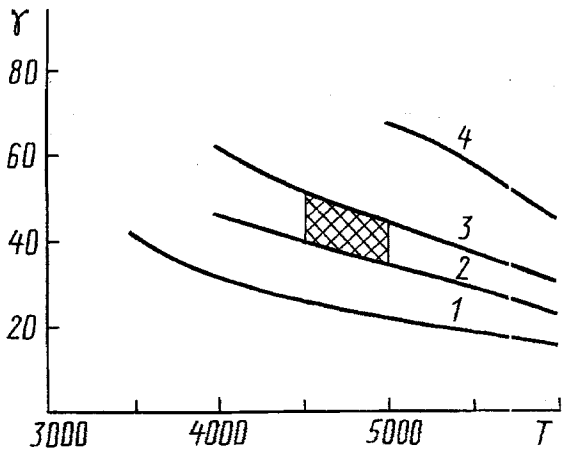

Fig. 3. Plot of the fraction of the energy supplied to plasma reactor spent on particle heating from initial plasma temperature. The charge-air mass ratio is 1 (1); 1.5 (2); 2 (3); 3 (4). γ, %; T, K.

Another factor which should be taken into consideration is the fraction of the plasma energy spent on heating the particles. In Fig. 3 is shown the part of the energy supplied to the reactor with a plasma flow that provides heating of the particles to 1400 K as a function of the initial plasma temperature.

One can see from the data presented that although heat treatment can be carried out at lower plasma temperatures, at a charge-gas ratio of 1, the thermal energy of the plasma is not used effectivity. In Fig. 3 the

cross-hatched area corresponds to conditions with plasma temperatures of 4500–5000 K and charge-gas mass ratios of 1.5 to 2. At $G_p/G_g = 1.5$ particles of up to 250 μm can be processed by plasma and to 200 μm at 4500 K; at $G_p/G_g = 2$, particles of up to 200 μm at 5000 K and to 150 μm at 4500 K can be processed. At $G_p/G_g = 5$ it is possible to process particles of up to 250 μm only at 6000 K, i.e., in comparison with the conditions shown in Fig. 3, the amount of energy spent on processing of one kilogram of charge has not decreased, nor has the fraction of effectively used energy increased. Thus, in plasma treatment of a vitrifying charge with a particle size of up to 250 μm, charge-gas mass ratios of 1.5 to 2 can be recommended. Under these conditions 35–50% of the plasma energy is used for heating the charge. The obtained estimates can be used for optimization of thermal processing of vitrifying charges in plasma reactors up to 200 kW. The present model should be developed further by refinement of the assumptions adopted.

NOTATION

B, shape factor of particles; C_D, air drag coefficient; d_{pl}, particle diameter; D, diameter of the channel of the reactor; G, mass flow rate; g, gravity acceleration; h, specific enthalpy; m, mass; n, the number of particles per unit volume; Q, heat flux; T, temperature; v, velocity; x, coordinate with the reference point on the axis of the channel; λ, thermal conductivity; μ, viscosity; ρ, mass density; $\rho_p = m_{pl} n_p$, density of the condensed phase. Subscripts: g, gas; pl, isolated particle; p, a set of particles; pr, gaseous and solid products of physicochemical transformations of the charge; w, walls of the reactor; 0, values of parameters in the inlet cross-section of reactor.

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