EFFECT OF DIFFERENT FACTORS ON COKE COMBUSTION IN A HIGHLY
CONCENTRATED POLYDISPERSE ASCENDING FLOW

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A study was made of the effect of ash content, the initial concentration of oxidant, and particle interactions on the parameters of the physicochemical processes occurring in the combustion of anthracite fines in a highly concentrated polydisperse ascending flow. The possibility of regulating the temperature of the gas-dust mixture is discussed.

The technology which currently holds the most promise for the use of low-grade fuels is their combustion in a circulating fluidized bed (CFB). One of the main elements of the combustion system in this case is the space under the bed, where a polydisperse collection of particles is burned in an ascending gas flow. A distinguishing feature of this operation is the high mass concentration of the solid phase. The high solid-phase concentration significantly intensifies the effects both of collisions of particles of different fractions with one another and collisions between these particles and the walls of the reactor. Thus, the temperature of the ash fractions should not exceed the temperature at which the ash begins to deform.

Intensive mixing of particles of the solid fuel and additions in a CFB and maintenance of the gas and ash temperatures at a level close to 900°C ensure efficient removal of oxides of sulfur. Proceeding on the basis of this, the temperature of the dust-laden flow in the reaction zone of the reactor during the combustion of high-sulfur fuels should be kept close to 900°C. In the combustion of low-sulfur fuels, the temperature should not exceed the softening point of the ash.

In the present investigation, we use the mathematical model in [2] to perform a numerical analysis of the effect of ash content, oxidant concentration in the gas mixture, and particle interactions on the degree of conversion and temperature of the gas flow, coke particles, and ash and the time the solid phase spends in the sub-bed space of the CFB. We will also analyze the feasibility of regulating T_a by changing the mass flow rate of the ash or the concentration of oxygen.

A polydisperse collection of coke and ash particles is characterized by a discrete distribution with respect to dimensions, i.e., we will be examining the fractions N_c and N_a, respectively. It is assumed that heterogeneous reactions between the coke and the gases occur on the outside surface of the impermeable spherical particles. The reaction rates were determined on the basis of the model of a "contracting" nonreactive core [3]. We will examine the case of the combustion of anthracite fines in clean air. Thus, only the heterogeneous reaction of coke particles with oxygen and carbon dioxide is considered in the stoichiometric reaction scheme:

$$C + O_2 = CO_2 + Q_1, \tag{1}$$

$$C + \frac{1}{2} O_2 = CO + Q_2, \tag{2}$$

$$C + CO_2 = 2CO - Q_3. \tag{3}$$

The mathematical flow model in [2] consists of a unidimensional steady-state system of "rigid" ordinary differential equations relative to w_g, $w_{\ell i}$ ($i = 1 - N_l$; l = c, a), T_g, $T_{\ell i}$, p, ρ_g, B_{ci}, C_m ($m = 1 - 4$, which corresponds to the components of the gas O_2, CO_2, CO, N_2). The model accounts for mass, momentum, and energy transfer in the gas and solid phases during heterogeneous reactions, convective interphase heat transfer, radiant heat

transfer between particles of coke and ash and the dust-laden flow, radiant and convective heat transfer between the flow and the walls of the reactor, mass transfer between the coke particles and the gas, gravitation, viscous drag on the reactor wall, aerodynamic resistance, and collisions between fractions. As an example, we present the equations for mass transfer in the gas phase and the motion of particles of the i-th fraction:

$$\frac{d}{dx}[(1-\beta)\,w_g C_m] = \sum_{i=1}^{N_c}(C_{mi}^0 - C_m)\frac{6\beta_{ci}\alpha_{mi}}{\delta_{\kappa i}}\ ; \tag{4}$$

$$\rho_{li}\frac{d}{dx}(\beta_{li}\omega_{li}^2) = -g\beta_{li}\rho_{li} + \frac{3}{4}\xi_{li}\rho_g|w_g - w_{li}|(w_g - w_{li}) - \frac{\beta_{li}}{\delta_{li}} -$$

$$-(1-\beta)\frac{f_{li}\rho_g w_g^2}{2d} +$$

$$+ \sum_{p=c,\,d}\sum_{j=1}^{N_p}\frac{9(1+k)\,m_{li}m_{pj}\beta_{li}\beta_{pj}(\delta_{li}+\delta_{pj})^2|w_{pj}-w_{li}|(w_{pj}-w_{li})}{2\pi\delta_{li}^3\,\delta_{pj}^3\,(m_{li}+m_{pj})}\ . \tag{5}$$

The last term in (5) accounts for interparticle interaction, which is described on the basis of the conditional substitution of continuously acting forces for a discrete process [4].

The system of equations was integrated by the Euler method. The steps were chosen automatically in relation to the number of iterations necessary to achieve the required accuracy for each parameter. We took the following values as the boundary conditions (inlet section of the flow): 1) the mass flow rate concentration of the solid phase μ_0 was varied from 10 to 50 with intervals $\Delta\mu_0 = 10$ (here, the coke concentration $\mu_{c0} = 0.4$); 2) the concentration of oxygen in the gas C_{10} was changed from 21 to 15%; 3) the velocity of the gases $w_{g0} = 4.5$ m/sec; 4) the temperature of the gas, ash, and coke $T_{g0} = T_{a0} = T_{c0} = 900°C$. We examined ten fractions of coke particles ($\delta_{c0} = 60; 100; 150; 200; 250; 300; 350; 400; 450; 500$ μm), and four fractions of ash ($\delta_a = 75; 150; 250; 350$ μm). The mass concentrations of the fractions of each substance were assumed to have been equal.

Figures 1-4 show some of the results of the calculations with (dashed lines) and without (solid lines) allowance for collisions between fractions. First let us examine the features of the process without allowance for the collisions. At $B_{c0} = $ const, an increase in ash flow leads to an increase in the amount of heat needed to heat it. Thus, the temperature of the coke particles decreases with an increase in μ_0 (curves 1-5, Fig. 1). The maximum reduction here occurs in the interval $\mu_0 = 10$-20. In this case, the difference in the maximum temperatures for particles $\delta_{c0} = 500$ μm (at x ~ 7 m) reaches 154 K. However, the rate of the change in temperature decreases sharply with a further increase in μ_0. This happens because the decrease in the thermal effects of the reactions is partially offset by a reduction in convective and radiative heat transfer from the coke particles (due to a reduction in the temperature heads $T_c - T_d$ and $T_c - T_g$). The difference in coke-particle temperature corresponding to the "adjacent" values of μ_0 increases with an increase in δ_{c0}, particularly in the interval $\mu_0 = 10$-20 (curves 1 and 2 in Fig. 1).

The rate of combustion of the coke fractions increases with an increase in δ_{c0} and a decrease in μ_0 (curves 1-5, Fig. 1). The maxima on the curves in the interval 6 < x < 8 m characterize equilibrium between the thermal effects of the reactions and heat transfer from the coke particles. Due to a decrease in the concentration of oxygen (Fig. 2) and an increase in the temperature heads $T_c - T_d$ and $T_c - T_g$, the heat-transfer rate becomes greater than the rate of heat release on the section x > 6-8 m and the coke particles undergo cooling (curves 1-5, Fig. 1a, and b). For fine particles ($\delta_{c0} = 60$ μm), the combustion rate is nearly constant over the entire length of the reactor (Fig. 1c). The results of the calculations show that two sections can be distinguished on the curves $T_c(x)$. On the initial section (not shown in Fig. 1), the temperature head $T_c - T_g$ is small, the rate of convective heat transfer is negligible, and the thermal state of the particles is determined mainly by heat release. As a result, the fines are hotter than the coarse fractions. The pattern subsequently changes — the effect of convection becomes significant (especially for the fines) and the temperature of the coarse particles on the second section of the reactor exceeds the temperature of the fine particles. Meanwhile, the largest temperature difference decreases sharply with an increase in μ_0 from 10 to 20; the change in the temperature gradient between the fractions slows considerably with a further increase in μ_0. The change in the temperature of the particles affects the degree of their conversion.
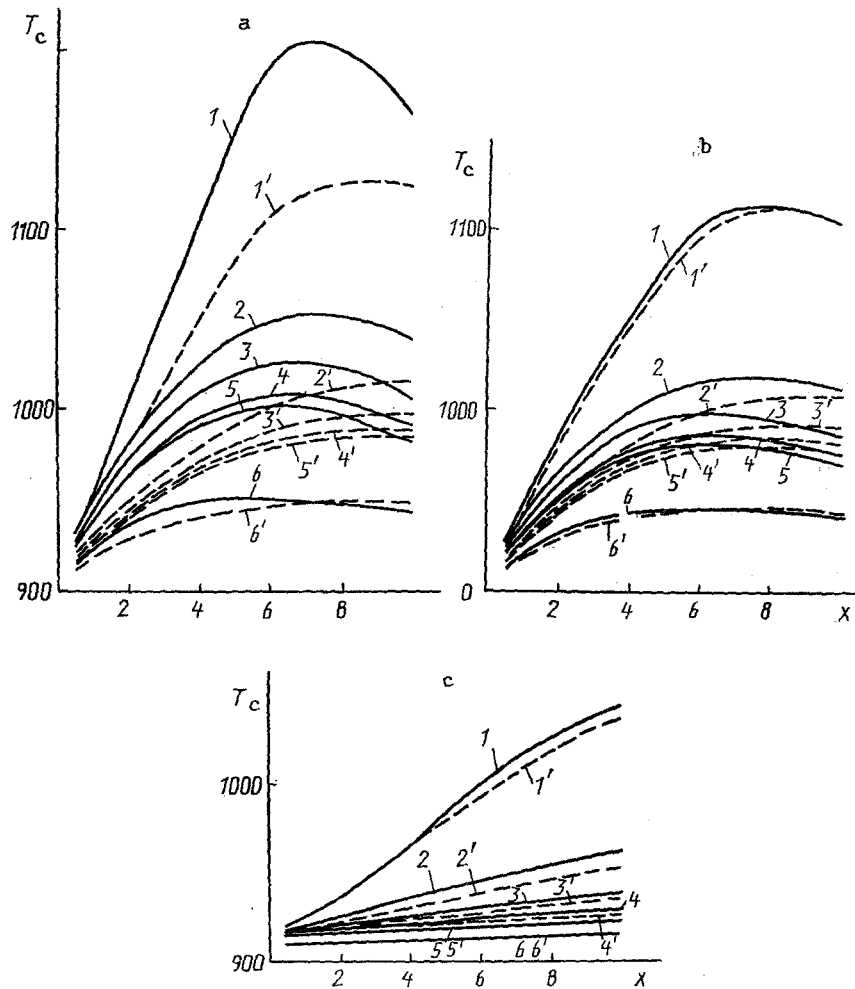
Fig. 1. Distribution of the temperature of coke particles over the height of the reactor: a) δ_c = 500 μm; b) 400; c) 60; 1, 1') μ_0 = 10; 2, 2') 20; 3, 3') 30; 4, 4') 40; 5, 5') 50; 6, 6') C_{10} = 15%, μ_0 = 40.
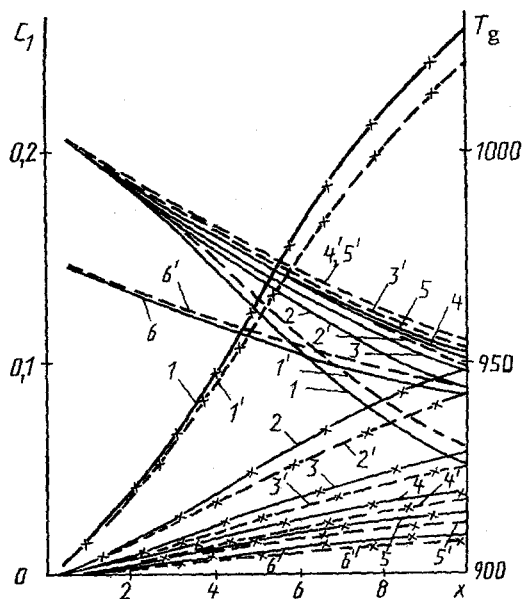

Fig. 2. Distribution of gas temperature (lines with points) and oxygen concentration over the height of the reactor (notation is the same as in Fig. 1).
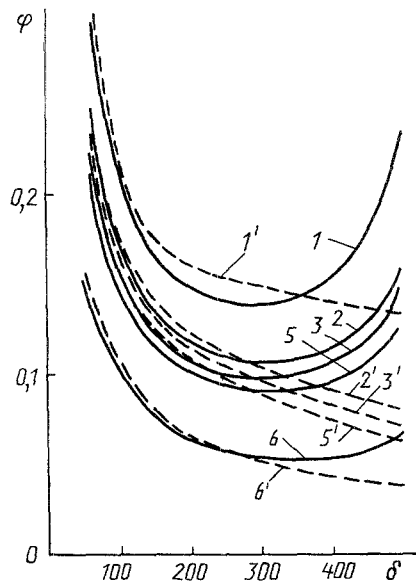
Fig. 3. Dependence of the degree of combustion of coke particles on their initial size (the notation is the same as in Fig. 1).

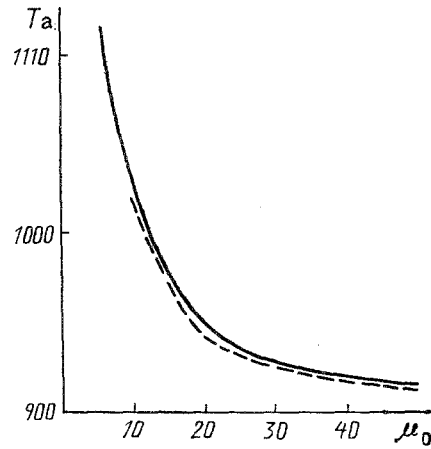Fig. 4. Dependence of the temperature of the ash particles on μ_0 at $\delta_a = 350$ μm, x = 10 m, $C_{10} = 21\%$.

Figure 3 shows the effect of the initial parameters (δ_{c0}, μ_0, C_{10}) on the degree of combustion φ. On the one hand, an increase in δ_{c0} is accompanied by a decrease in the specific reaction surface of the particles. On the other hand, an increase in δ_{c0} is accompanied by an increase in the residence time of the particles in the reaction zone (due to a decrease in their velocity). The first factor is dominant in the interval $60 < \delta_{c0} < 300$ μm, while the second factor is dominant on the ascending branch. An increase in μ_0 has an adverse effect on combustion efficiency (due to a reduction in the rates of the reactions), with the most appreciable decrease in the degree of conversion occurring in the interval $\mu_0 = 10\text{-}20$.

It is evident from Fig. 2 that the concentration of oxygen C_1 decreases along the reactor due to heterogeneous reactions (1) and (2), while the temperature of the gases T_g increases. Meanwhile, an increase in μ_0 is accompanied by an increase in C_1 and a decrease in T_g.

Figure 4 shows the effect of the concentration of the solid phase on the temperature of the ash particles. The exponential decrease in T_a is caused by a reduction in the amount of heat received by the ash particles due to convection and radiation. This relationship can be used to control temperature in boilers with a CFB. It is apparent from Fig. 4 that a substantial reduction in temperature is seen in the interval $\mu_0 = 0\text{-}35$, while a further increase in μ_0 has little effect on T_a. Thus, at high μ_0, temperature should be regulated by another method — changing the initial concentration of oxygen in the gas flow. A decrease in C_{10} to 15% (curve 6, Fig. 2) leads to a decrease in the heating effects of the reactions. As a result, the temperature of the coke fractions declines (curve 6, Fig. 1). This in turn entails a decrease in the degree of conversion, gas temperature (Figs. 2 and 3), and the temperature of the ash particles. The latter quantity nearly coincides with T_g in this instance.

It follows from a comparison of the two methods of temperature regulation that the last variant more efficiently lowers the temperature of the ash fractions. However, the attendant reduction in coke combustion may lead to an increase in the amount of heat lost with mechanical underfiring, which will in turn adversely affect the efficiency of the reactor. Thus, the choice of the method of temperature control must be made on the basis of a technical—economic comparison of the variants in each specific case.

It is evident from Fig. 1 (curves 1'-6') that interactions between particles help lower the temperature of the fractions — especially for the coarse particles ($\delta_{c0} = 500$ μm). As was shown by the calculated results, the velocities of the fine fractions ($\delta_{c0} = 60\text{-}270$ μm) decreases due to the collisions, while the velocities of the coarse fractions ($\delta_{c0} = 270\text{-}$

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500 μm) increases. As a consequence of this, the residence time of the fine particles is increased somewhat, while that of the coarse particles decreases. Convective heat transfer from particles δ_{c0} = 500 and 400 μm to the gas decreases due to a decrease in the temperature head $T_c - T_g$ and the heat-transfer coefficient. However, this only partially compensates for the more substantial reduction in the thermal effects of the reactions. Thus, the ultimate result is a decrease in T_c (curves 1'-6', Fig. 1a, 1b). It is evident from Fig. 1a that the decrease in T_c under the influence of interparticle collisions is greater, the lower the total concentration of particles μ_0. This linkage can be attributed to the fact that, other conditions being equal, an increase in μ_0 is accompanied by a decrease in T_c (see above). This result in turn lowers the reaction rates, so that heat release begins to depend less on the residence time of the particles in the reaction zone.

Equalization of the velocities and residence times of the coke particles δ_{c0} = 500 and 400 μm helps reduce the temperature difference between these fractions. Thus, at μ_0 = 10 (x ~ 7 m), the temperature gradient decreases from 94 K (curves 1, Fig. 1a, 1b) to 14 K (curves 1', Fig. 1a, 1b). Meanwhile, the temperature of the particles δ_{c0} = 500 μm remains higher than that of the particles δ_{c0} = 400 μm over the entire length of the reactor. At high μ_0, the difference between the velocities of these fractions (with allowance for collisions) decreases. Thus, on the first section (0 < x < 5.5 m) — where intensive combustion takes place — the temperature of the particles δ_{c0} = 400 μm is higher than the temperature of the particles δ_{c0} = 500 μm (curves 2'-5', Fig. 1a, 1b). Then (x > 5.5 m) a decrease in C_1 and an increase in the temperature heads cause heat transfer to begin to have a greater effect on the thermal state of the particles than the thermal effects of the reactions. The lesser effect of heat from the reactions is particularly noticeable for the fraction δ_{c0} = 400 μm. Thus, the temperature of the particles δ_{c0} = 400 μm turns out to be lower than the temperature of the particles δ_{c0} = 500 μm. The temperature of the fine particles (δ_{c0} = 60 μm) decreases by a negligible amount.

Allowance for collisions leads to a marked change in the degree of conversion (see Fig. 3) — the main factor in this case is the change in particle residence time in the flow. While a slight increase in φ, is seen in the left region bounded by the points of intersection of the solid and dashed lines in Fig. 3 at μ_0 = const, a substantial decrease in is observed in the right region. Here, the effect of collisions for the coarse particles is so great that the character of the curves is changed — the relation $\varphi(\delta_{c0})$ becomes monotonically decreasing throughout the investigated range. It should also be noted that a low concentration correlates with the maximum value of the abscissa of the point of intersection of the curves ($\delta_{c0} \approx$ 370 μm).

It follows from a comparison of the area under the curves in Fig. 3 with fixed μ_0 that allowance for interparticle collisions decreases the total degree of combustion. Thus, on the one hand, gas temperature (due to a decrease in convective heat transfer from the coke particles) and the consumption of oxygen in reactions (1) and (2) decreases (Fig. 2). On the other hand, there is a decrease in the amount of heat delivered to the ash particles by convection and radiation. This helps lower the temperature of these particles (Fig. 4).

The completed calculations show that the temperature characteristic of the phases, the degree of conversion, and other important parameters of highly concentrated polydisperse flows with hot coke particles are determined mainly by the ash content of the material and the concentration of oxidant. By changing these parameters, it is possible to efficiently regulate the temperature of the dust-gas flow. These results are of interest for the development of a promising new method of burning low-grade fuels in a circulating fluidized bed.

Notation. T, temperature; N, number of fractions; Q, thermal effect of the reactions; w, velocity; p, pressure; ρ, density; B, mass flow rate; C_m, C_m^0, concentration of the m-th component of the gas in the volume and on the surface of a particle; x, longitudinal coordinate; β, true volume concentration; δ, size of particles; α, mass-transfer coefficient; g, acceleration due to gravity; ξ, drag coefficient of particles; f, coefficient of friction of particles against wall; d, diameter of reactor; m, mass of a particle; k, coefficient of restitution of the normal components of the velocities in a collision; μ, mass flow rate concentration; $\varphi = 1 - B_{ci}/B_{ci0}$, degree of combustion of coke particles. Indices: 0, inlet section of the flow; g, gas; c, coke; a, ash; d, dust-laden flow; i, j, numbers of particle fractions; l, p, designation of "type" of particle (l, p = c, a); m, number of component of the gas.

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DECAY OF ELECTRIFIED ROTATING CAPILLARY JETS

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A study was made of the effect of electrification and rotation of the nonmonodisperse decay of capillary jets. The study was conducted within the framework of the complete system of equations of hydrodynamics by the Bubnov–Galerkin method.

The organization of a monodisperse spray is extremely important in a number of processes which take place in the power-generation and construction industries and in various types of sprayers commonly used in agriculture and other sectors. Here, an important role is played by the electrification of capillary jets [1-10]. Well-known theoretical studies have focused mainly on linear [1-6], weakly nonlinear [7], or finite-amplitude [10] stability in quiescent electrified jets.

In the present investigation, we examine the effect of rotation on the nonmonodisperse atomization of electrified capillary jets.

We will assume that the liquid is inviscid, incompressible, and ideally conducting. We will further assume that the flow inside the jet is a potential flow. The velocity potential of the main flow and the potential of a charged circular cylinder φ_0 have the form

$$\Phi_0 = \Gamma\theta/(2\pi), \quad \varphi_0 = A \ln(r/a).$$

The equations, the boundary conditions, and the initial conditions appear as follows in dimensionless variables [10, 11]:

$$\Delta\Phi = 0 \ (0 \leqslant r \leqslant r_* \equiv 1 + \xi) \ \Delta\varphi = 0 \ (r \geqslant r_*); \tag{1}$$

$$\xi_t = \Phi_r - \xi_z\Phi_z, \quad \varphi = 0 \ (r = r_*, \ r \to \infty); \tag{2}$$

$$\Phi_t = -\frac{1}{2}\left[\Phi_r^2 + \Phi_z^2 + \omega\left(\frac{1}{r^2} - 1\right)\right] - (\varkappa - 1) + b(t)[\varphi_n^2 - 1](r - r_*); \tag{3}$$

$$\xi(z, 0) = \xi_0(z), \quad \Phi(r, z, 0) = \Phi_0(r, z). \tag{4}$$

Here, $\varkappa \equiv [1 + \xi_z^2]^{-3/2}\left\{\left[\dfrac{1 + \xi_z^2}{1 + \xi}\right] - \xi_{zz}\right\}$, $b(t) = \left(\dfrac{a^2}{2\pi Ta}\right) = q^2\pi$, $\omega = \dfrac{\Gamma^2\rho^1}{(2\pi^2 Ta)}$; φ is the perturbation of electric potential; $Q(t)$ is the surface charge per unit length of the jet at the given moment of time.

Conditions reflecting the boundedness of the perturbations of all of the physical quantities must also be satisfied.

We will use the method described in [10] to solve the stated problem. The sought solution is represented in the form