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CALCULATING SOLID-FUEL CONSUMPTION IN A CIRCULATION SYSTEM

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UDC 536.46

A size-distribution equation is used in deriving the burning rate for a polydisperse solid fuel subject to repeated external circulation through a cyclone. The effects from fuel fractional composition and cyclone parameters are examined.

Recently, increasing use has been made of systems for burning solid fuel involving repeated circulation through a cyclone (Fig. 1), as with a circulating fluidized bed [1] or in an air jet furnace [2]. Fresh fuel is supplied to the combustion chamber from a dust-handling device at a rate G_{a0}, while partially burned (secondary) fuel is fed from the cyclone at a rate G_{ac}, i.e., $G_a = G_{a0} + G_{ac}$. The fuel entering the cyclone from the combustion chamber G_b passes through it and returns to the combustion chamber as $G_{ac} = G_b - G_c$, with the exception of the part G_c that is not trapped is lost from the system. G_c/G_b is dependent on the cyclone's performance and governs the mechanical incompleteness in the combustion.

It is difficult to perform calculations on such burning because the fuel fractional composition (size distribution) at the inlet to the combustion chamber is not known in advance and is depend on the composition of the cyclone material, i.e., on the size distribution for the particles entering the cyclone and the characteristics of the latter. The size distribution at the inlet is thus dependent on that at the outlet, and in that sense, the combustion is a self-consistent system; even if the input from the dust preparation device was monodisperse, the repeated circulation makes it polydisperse.

1. We consider coke particles burning in an air flow, with the particle density ρ_2 unaltered during the combustion. To consider a polydisperse system, we consider the kinetic equation for the size distribution used in [3, 4 for combustion in an ordinary chamber with-

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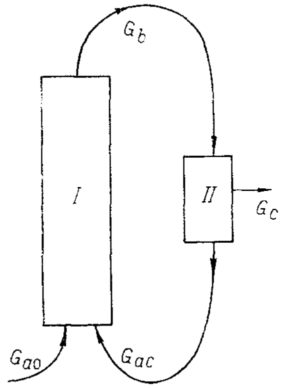

Fig. 1. Fuel motion in circulation system: I) combustion chamber; II) cyclone.

out fuel circulation. We use a one-dimensional approximation on the length (height) of the combustion chamber, which has a constant cross section, i.e., the flow parameters transverse to that chamber are taken as unchanging. Then the size distribution equation is

$$\frac{\partial vP}{\partial x} - \frac{\partial wP}{\partial r} = 0. \tag{1}$$

The density P is normalized to

$$\int_0^\infty P dr = n.$$

To construct an analytic solution, we average v and w in (1), which gives

$$\frac{\partial VP}{\partial x} - \frac{\partial WP}{\partial r} = 0, \tag{2}$$

in which

$$V = \int_0^\infty vr^3 P dr \Big/ \int_0^\infty r^3 P dr; \quad W = \int_0^\infty wr^2 P dr \Big/ \int_0^\infty r^2 P dr.$$

We average v and w in such a way that (2) leads to the same equation for the particle mass variation as does the exact (1):

$$\frac{dV\varphi}{dx} = -nSW, \tag{3}$$

in which

$$\varphi = \frac{4}{3}\pi \int_0^\infty r^3 P dr; \quad S = \frac{4\pi}{n} \int_0^\infty r^2 P dr.$$

The solution to (2) satisfying the size distribution at the input $P_a\{r\}$ at x = 0 is

$$P = \frac{V_a}{V} P_a\{r + l\}, \quad l = \int_0^x \frac{W}{V} dx, \tag{4}$$

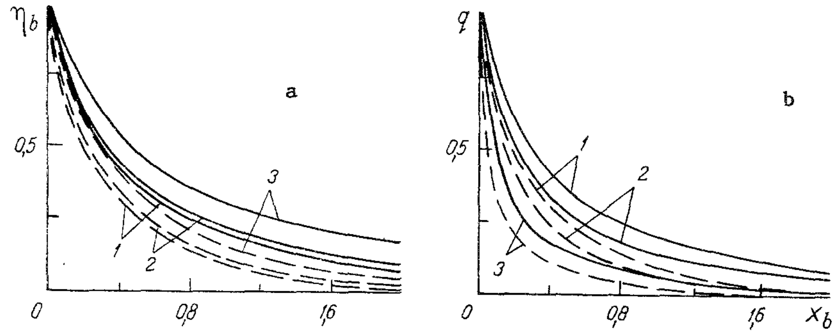

Fig. 2. Burn-up coefficients (a) and mechanical underburning coefficients (b) for a monodisperse system as of (20) with r_c = 0: 1) $\varkappa$ = 0; 2) 0.8; solid lines α_0 = 1; dashed lines 1.2.

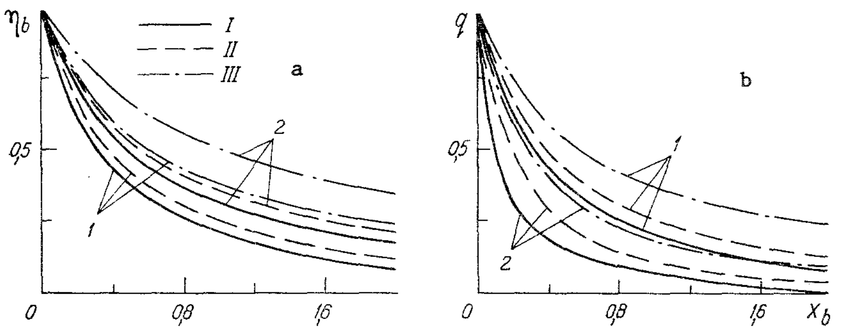

Fig. 3. Comparison of burn-up coefficients (a) and mechanical underburning coefficients (b) for various initial size distributions with r_c = 0 and α_0 = 1.0; I) (20), II) (21), III) (22); 1) $\varkappa$ = 0; 2) 0.8.

where ℓ defines the maximum initial radius as a particle moves from the inlet to the section x, while the braces denote a functional relationship.

Then (4) gives the size distribution at the outlet from the chamber as

$$P_b\{r\} = \frac{V_a}{V_b} P_a\{r + L\}, \quad L = \int\limits_0^{x_b} \frac{W}{V}\, dx. \tag{5}$$

The inlet distribution is the sum of those for the fuel input from the dust and from the cyclone, i.e.,

$$P_a\{r\} = P_{a0}\{r\} + P_{ac}\{r\}, \tag{6}$$

in which $P_{a0}\{r\}$ is taken as known.

The distribution for the fuel entering from the cyclone is related to that for fuel leaving the combustion chamber by

$$P_{ac}\{r\} = F\{r\} P_b\{r\}, \tag{7}$$

in which F{r} is a function that is taken as known, which describes the cyclone particle separation, i.e., the size transformation.

We get from (5)-(7) a formula for the distribution at the combustion-chamber outlet:

$$P_b\{r\} = \frac{V_a}{V_b}[P_{a0}\{r + L\} + F\{r + L\} P_b\{r + L\}]. \tag{8}$$

Here (8) is a functional equation with displaced argument. It gives all the burning characteristicss if V_a/V_b and L are known; it is solved by iteration to give

$$P_b\{r\} = \sum_{k=0}^{\infty} \left(\frac{V_a}{V_b}\right)^{k+1} \prod_{m=1}^{k} F\{r+mL\}\, P_{a0}\{r+(k+1)L\}. \tag{9}$$

The combustion-chamber inlet-section size distribution is given by (5) and (9) as

$$P_a\{r\} = \sum_{k=0}^{\infty} \left(\frac{V_a}{V_b}\right)^{k} \left(\prod_{m=0}^{k-1} F\{r+mL\}\right) P_{a0}\{r+kL\}. \tag{10}$$

The physical significance of (9) and (10) is obvious: there is summation over the number of cycles performed by particles, and as $P_{a0}\{r\}$ satisfies $\int_0^{\infty} P_{a0}dr = n_{a0}$, the series in (9) and (10) converge at least on average [5].

A simple approximation for F{r} is

$$F\{r\} = \varkappa\xi(r-r_c), \quad \xi(r-r_c) = \begin{cases} 0 & \text{for } r<r_c, \\ 1 & \text{for } r \geqslant r_c, \end{cases} \tag{11}$$

which describes the removal of small fractions $r < r_c$ in the cyclone, which are not recycled, and the resultant reduction in the residual-particle spectrum is proportional to the coefficient $\varkappa$ as a result of the separation loss. Then (10) becomes

$$P_a\{r\} = \zeta(r-r_c)\, P_{a0}\{r\} + \xi(r-r_c) \sum_{k=0}^{\infty} \left(\frac{V_a}{V_b}\varkappa\right)^{k} P_{a0}\{r+kL\}, \tag{12}$$

in which $\zeta(r-r_c) = 1-\xi(r-r_c)$.

The burning rate in the combustion chamber is

$$\eta = \frac{G}{G_a} = \frac{V\varphi}{V_a\varphi_a} = \frac{\int_0^{\infty} r^3 P_a\{r+l\}\, dr}{\int_0^{\infty} r^3 P_a\{r\}\, dr}, \tag{13}$$

which is equal to the ratio of the flow rate in the section x to the entering flow rate. The burn-up factor is then

$$\eta_b = \frac{G_b}{G_a} = \int_0^{\infty} r^3 P_a\{r+L\}\, dr \Big/ \int_0^{\infty} r^3 P_a\{r\}\, dr \tag{14}$$

and characterizes the turning rate in the combustion chamber in a cycle.

The cyclone's performance is

$$K = \frac{G_{ac}}{G_b} = \frac{V_a \int_0^{\infty} r^3 F\{r\}\, P_b\{r\}\, dr}{V_b \int_0^{\infty} r^3 P_b\{r\}\, dr}, \tag{15}$$

which is the ratio of the flow rates for the fuel passing from the cyclone to the combustion chamber and the total fuel reaching the cyclone from it. For K = 0, there is no recirculation, and the system is open-loop. For K = 1, there is no loss in the cyclone, so the mechanical underburning is zero.

The mechanical underburning coefficient q is defined as the ratio of the flow rates of the material lost in the cyclone and entering from the dust handler, i.e., $q = G_c/G_{a0}$; it characterizes the joint work of the two and can be expressed in terms of η_b and K: $q = \eta_b (1-K)/(1-\eta_b K)$.

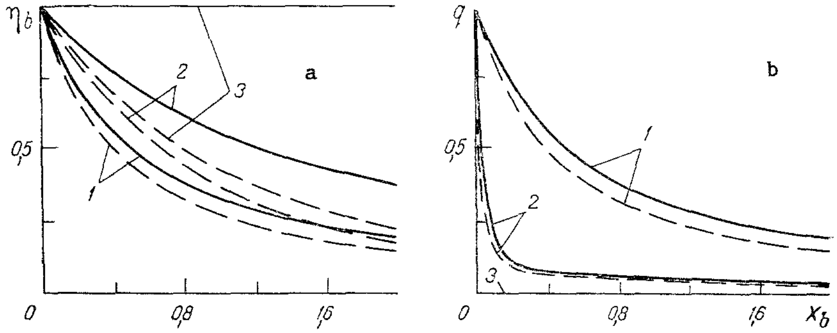

Fig. 4. Burn-up coefficients (a) and mechanical underburning coefficients (b) for the (22) exponential distribution for $\varkappa = 1$: 1) $\bar{r}_C = \infty$; 2) 1; 3) 0; solid lines $\alpha_0 = 1$, dashed lined 1.2.

2. We consider coal particle combustion by oxidation: $C + O_2 = CO_2$. The equation for the oxygen concentration along the combustion chamber is

$$\frac{dU\rho_1 C}{dx} = -\frac{\mu_{O_2}}{\mu_C}\rho_2 nSW. \tag{16}$$

Then (3) and (16) define a relation between the oxygen concentration and the fuel burning rate:

$$C = \frac{\mu_{O_2}}{\mu_C}\frac{V_a\rho_2\varphi_a}{U\rho_1}(\eta+\alpha-1) = \frac{\mu_{O_2}}{\mu_C}\frac{G_a}{G_{a0}}\frac{V_a\rho_2\varphi_{a0}}{U\rho_1}\left(\eta+\frac{G_{a0}}{G_a}\alpha_0-1\right), \tag{17}$$

in which $\alpha=\mu_C U_a\rho_{1a}C_a/\mu_{O_2} V_a\rho_2\varphi_a$ is the excess-air coefficient at the inlet section, while $\alpha_0=\mu_C\tilde{U}_a\rho_{1a}C_a/\mu_{O_2} V_a\rho_2\varphi_{a0}$ is the same in the inlet section as referred to the fuel flow rate from the dust handler, and $G_{a0}/G_a = 1 - \eta_b K$.

To establish the main effects from the initial size distribution $P_{a0}\{r\}$ and from the cyclone characteristics, we performed calculations for the case where the particle speed and combustion were independent of radius and did not vary along the combustion chamber, which can occur for sufficiently small particles burning under kinetic conditions in an isothermal chamber. In that case, the burning rate varies only as a result of the reduction in oxygen concentration along the chamber, i.e.,

$$W = \frac{\mu_C\rho_1}{\mu_{O_2}\rho_2}kC, \tag{18}$$

and $V = V_b = V_a$, $U = U_a$.

The equation for the maximal initial radius of the burning particles is given by (4), (17), and (18) in dimensionless form as

$$\frac{d\bar{l}}{dX} = \frac{\eta+(1-\eta_b K)\alpha_0-1}{1-\eta_b K}. \tag{19}$$

One calculates the combustion on that basis by integrating (13)-(15) and (19), where the distributions $P_a\{r\}$ and $P_b\{r\}$ are defined by (9) and (10). Calculations have been performed for monodisperse, uniform, and exponential initial distributions $f_0\{\bar{r}\}=P_{a0}\{\bar{r}\}/n_0$ for a cyclone in which (11) describes the separation. The burning characteristics for the various initial $f_0\{\bar{r}\}$ were compared for identical concentrations φ_{a0} and mean-mass particle sizes r_{a0} in the inlet section, and thus for identical n_{a0}, since $\varphi_{a0}=4\pi r_{m0}^3 n_{a0}/3$; $f_0\{\bar{r}\}$ satisfy $\int_0^\infty f_0 d\bar{r} = \int_0^\infty \bar{r}^3 f_0 d\bar{r} = 1$. Expression (12) correspondingly takes the following forms:

1) monodisperse system

$$f_0\{\bar{r}\} = \delta(\bar{r}-1),$$

$$P_a\{\bar{r}\} = n_{a0}\left[\delta(\bar{r}-1) + \xi(\bar{r}-\bar{r}_c)\sum_{k=1}^{h}\varkappa^k\delta(\bar{r}+k\bar{L}-1)\right], \tag{20}$$

in which h is the integer part of $1/\bar{L}$;

2) uniform size distribution:

$$f_0\{\bar{r}\} = 4^{-1/3}\zeta(\bar{r}-4^{1/3}),\quad P_a\{\bar{r}\} = n_{a0}4^{-1/3}\left[\zeta(\bar{r}-4^{1/3}) + \xi(\bar{r}-\bar{r}_c)\sum_{k=1}^{h}\varkappa^k\zeta(\bar{r}+k\bar{L}-4^{1/3})\right]; \tag{21}$$

3) exponential distribution

$$f_0\{\bar{r}\} = 6^{1/3}\exp(-6^{1/3}\bar{r}),\quad P_a\{\bar{r}\} = n_{a0}6^{1/3}\exp(-6^{1/3}\bar{r})\left[\zeta(\bar{r}-\bar{r}_c) + \frac{\xi(\bar{r}-\bar{r}_c)}{1-\varkappa\exp(-6^{1/3}\bar{L})}\right]. \tag{22}$$

Figures 2-4 show results on η_b and q as functions of the combustion-chamber height X_b for various values of the cyclone parameters $\varkappa$, and $\bar{r}_c$ together with α_0. Naturally, the first two decrease as X_b increases because the particle residence time in the combustion chamber increases. Also, they decrease as the excess air coefficient increases because of the elevated oxygen concentrations and combustion rates.

When K increases, which occurs if $\varkappa$ increases ($K=V_a\varkappa/V_b$ for $\bar{r}_c = 0$) or $\bar{r}_c$ decreases, one gets a reduced burning rate cycle, which is due to reduction in the excess air coefficient with α_0 unaltered on account of the elevated fuel flow rate from the cyclone. For K = 1 and $\alpha_0 < 1$, the lack of oxygen means that the mass of fuel burned in unit time is less than the flow of fresh fuel, which leads to an unbounded increase in the flow rate for the secondary fuel, and $\eta_b \to 1$ for $\alpha_0 \to 1$. Consequently, for K close to one, where there is repeated recirculation, the combustion should be organized with α_0 greater than one. As K increases, q naturally decreases although the burning per cycle is reduced, i.e., there is repeated circulation in the system as a whole.

Figure 3 compares the characteristics for several initial size distributions. The relation between the characteristics for the various $f_0\{\bar{r}\}$ persists for all values of the parameters, i.e., the (20) monodisperse system burns most vigorously, and the exponential (22) the least. The quality of the $f_0\{\bar{r}\}$ distribution is characterized by $\sigma = \int_0^\infty \bar{r}^2 f_0 d\bar{r}$, which is proportional to the mean particle surface, since (3) shows that the burning rate is proportional to the latter. The larger σ, the more rapid the burning. The maximum value σ = 1 orrurs for the monodisperse system, while σ for (21) and (22) are correspondingly $4^{1/3}/3/^2 \approx 0.917$ and $2/6^{2/3} \approx 0.616$.

This method of calculating a circulation system can be extended without essential difficulty to more complicated cases: incorporation of the diffusion resistance and several heterogeneous reactions, nonisothermal flow, etc.

NOTATION

G, fuel flow rate; x, coordinate along combustion chamber; r, particle radius; v, speed of particles with radius r; w, burning rate for particles with radius r; V, mean particle speed; W, mean burning rate; n, number of particles in unit volume; φ, volume particle concentration; S, mean particle surface; U gas speed; C, mass oxygen concentration in gas; x_b, length (height) of combustion chamber; ρ_1 and ρ_2, gas and particle densities; μ_{O_2}, μ_C molecular masses of oxygen and carbon; k, burning rate constant; r_{a0}, mean-mass particle radius; $\bar{l}=l/r_{a0}$; $\bar{L}=L/r_{a0}$; $\bar{r}=r/r_{a0}$; $\bar{r}_c=r_c/r_{a0}$; $\bar{X}=x\varphi_{a0}k/U_a r_{a0}$. Subscripts; a, inlet to combustion chamber; b, outlet from combustion chamber; c, cyclone; 0, dust-handling device.

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MUTUAL GAS DISPLACEMENT FROM A POROUS MEDIUM UNDER CHEMICAL REACTIONS CONDITIONS

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Equations are derived that describe the technological process of natural underground sulfur-cleaning of natural gases containing hydrogen sulfide during their passage through a chemically active porous medium, and exact solutions are obtained of model problems.

One of the promising methods of developing low-sulfur natural gas deposits is the method of underground sulfur-cleaning [1, 2]. The crux of the method is to pass the gas containing the hydrogen sulfide through the stratum whose rock has iron oxide in its composition. Cleaning of the gas occur because of the chemical reaction between the hydrogen sulfide and the iron oxides. The quantity of extractive and bypassing boreholes assuring cleaning of the requisite quantity of gas in a given time, the distance between the boreholes and the depressions in the stratum must be determined to plan this development method. This is performed on the basis of mathematical modeling data [3].

Models of two-phase filtration under chemical reaction conditions between the phases and the skeleton are proposed in [4, 5], and self-similar solution are obtained for frontal displacement problems.

Filtration equations are derived in this paper for a gas containing hydrogen sulfide in a water-saturated medium under chemical reaction conditions with ferric and ferrous oxides in the rock. An exact solution is obtained for the one-dimensional problem describing the displacement of a sulfur-free gas by one containing hydrogen sulfide from a porous medium in whose composition are iron oxides. The problem of migration of the gas containing the hydrogen sulfide into the sulfur-free part of the deposits under chemical reaction conditions is solved.

Analogous problems occur in the investigation of underground leaching problems for metals [6], gypsum [7], underground extraction of sulfur [8], geochemistry and hydrogeology [9].

1. PHYSICOCHEMICAL TRANSFORMATIONS IN A POROUS MEDIUM

Upon injection of a low-sulfur gas into a porous medium whose rock contains iron oxides in its composition, dissolution of the hydrogen sulfide from the gas into the residual water and its chemical reactions with the ferrous FeO and ferric Fe_2O_3 oxides occur (Fig. 1).

The intensity of the hydrogen sulfide mass transfer between the gas and water phases q is given by the Gibbs law [10, 11]

$$q = \lambda (s_*) [\mu_g (c, p) - \mu_w (c, p)]. \quad (1)$$

Water is the catalyst for the chemical reactions between H_2S and the iron oxides, these reactions do not occur unless it is present [2].

Reaction between the hydrogen sulfide and iron oxide results in the formation of iron sulfide and water

$$FeO + H_2S \rightarrow FeS + H_2O. \quad (2)$$

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