
STEAM BOILERS, POWER-GENERATING FUEL, BURNERS, AND BOILER AUXILIARY EQUIPMENT

Modeling the Burnout of Solid Polydisperse Fuel under the Conditions of External Heat Transfer

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Abstract—A self-similar burnout mode of solid polydisperse fuel is considered taking into consideration heat transfer between fuel particles, gases, and combustion chamber walls. A polydisperse composition of fuel is taken into account by introducing particle distribution functions by radiuses obtained for the kinetic and diffusion combustion modes. Equations for calculating the temperatures of particles and gases are presented, which are written for particles average with respect to their distribution functions by radiuses taking into account the fuel burnout ratio. The proposed equations take into consideration the influence of fuel composition, air excess factor, and gas recirculation ratio. Calculated graphs depicting the variation of particle and gas temperatures, and the fuel burnout ratio are presented for an anthracite-fired boiler.

Keywords: modeling, combustion, solid fuel, polydisperse composition, distribution function, combustion modes

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One of the methods used to fire natural solid fuel (coal) in furnace devices is its combustion in pulverized form. In this case, aerosuspension is supplied to the burners, which consists of a mixture of air and polydisperse pulverized coal. Combustion of pulverized fuel is a complex set of physicochemical phenomena, such as heat transfer between particles, gases, and enclosing surfaces, release of moisture and volatiles in the course of heating, combustion of volatiles and coke residue accompanied by a multitude of various reactions and intense mass transfer, conversion of the fuel mineral part, etc. These processes may run either sequentially in time or concurrently with each other and have a strong influence on each other. In this connection, those carrying out a theoretical analysis face the need to simultaneously consider equations describing the motion of gases with particles, heat transfer between particles, gases, and walls, chemical kinetics that takes into account, apart from coke residue combustion, also the release and combustion of volatiles, etc. Since some processes are still poorly understood, we can state that it is almost impossible to construct an exact mathematical model, and an attempt to decrease the number of simplifying assumptions will inevitably result in obtaining an excessively complicated model. Thus, we should take only those simplifying assumptions that do not have an essential effect on the main processes and that will allow us to obtain satisfactory agreement between calculation and experiment.

A polydisperse composition of fuel gives rise to certain difficulties in calculating a pulverized coal flame. The sizes of pulverized fuel obtained in milling coal

may differ from one another by as much as one or two orders of magnitude. Since the intensity of heat transfer between particles, gases, and enclosing surfaces, release of volatiles, and other processes depend on the size of particles, particles belonging to different fractions burn under different conditions. Fine fractions are heated and ignited more rapidly than large fractions, thus increasing the general temperature level in the system and consuming part of oxidizer. It should also be pointed out that both sizes of particles and their quantity vary during the combustion process.

Matters concerned with studying the combustion of polydispersed solid fuel systems were addressed in many works. In some studies [1, 2], polydispersed composition was taken into account by introducing a conditional “monodispersed” system averaged according to the initial distribution function based on the Rosin–Rammler law, whereas other researchers [3] took polydispersity into account by subdividing a system into certain number of fractions with finding the average size within each of them. The authors of [3] stated and solved problems concerned with analyzing the ignition and burnout of both individual particles and “monofractions” at short process periods. To this end, systems of equations written for each fraction were solved numerically.

Application of a statistical approach to solving the problems concerned with combustion of polydispersed pulverized coke, central to which is solution of the kinetic equation for the particle distribution function by radiuses [4, 5], made it possible to boil down the problem to solving the equations for the particle size averaged over the distribution function.

In [4], the following basic correlations for calculating the fuel particle burnout ratio y were obtained:

$$y = \frac{M_p}{M_{p0}} = \exp\left(a \int_0^\tau \omega(\tau) d\tau\right), \quad (1)$$

where M_p and M_{p0} are the current and initial masses of all particles, a is the separation constant in integrating the kinetic equation for the particle distribution function by radiuses using the Fourier method, $\omega(\tau)$ is the combustion rate time part, and τ is time.

From (1) we can write the differential equation for determining y :

$$\frac{dy}{d\tau} = a\omega(\tau)y. \quad (2)$$

The particle combustion rate $W(r, \tau)$ is determined for the diffusion-kinetic model in the form

$$W(r, \tau) = \frac{dr}{d\tau} = -\frac{\beta C_{ox}}{\left(\frac{1}{K} + \frac{1}{\alpha_d}\right)\rho_p} \frac{273}{T_g}, \quad (3)$$

where r is the current particle radius, C_{ox} is the current concentration of oxygen recalculated for the standard temperature and pressure, ρ_p is the density of particles, β is the reaction stoichiometric coefficient, $K = k_0 \times \exp\left(-\frac{E}{RT_p}\right)$ is the chemical reaction kinetic rate constant, k_0 is the exponent multiplier, R is the universal gas constant, E is the activation energy, T_p and T_g are the temperatures of particles and gas, $\alpha_d = \frac{Nu_d D}{2r}$ is the diffusion transfer coefficient, Nu_d is the Nusselt diffusion number, $D = D_0 (T_g/273)^m$ is the diffusion coefficient, D_0 is the diffusion coefficient at standard temperature and pressure, and the exponent $m = 1.5-2.0$.

The particle distribution functions by their radiuses and the self-similarity parameters are given by

for a diffusion combustion mode ($K \gg \alpha_d$) when there is no phase slipping ($Nu_d = 2$)

$$f_0(r) = ar \exp\left(-a \frac{r^2}{2}\right); \quad a = \frac{2\Gamma^2(3/2)}{\langle r \rangle_0^2};$$

$$\langle r^n \rangle = \langle r^n \rangle_0 = \frac{\langle r \rangle_0^n \Gamma\left(\frac{n+2}{2}\right)}{\Gamma^n(3/2)}, \quad (4)$$

where $f_0(r)$ is the initial distribution function, $\Gamma(z)$ is the gamma function, $\langle r^n \rangle$, $\langle r^n \rangle_0$, $\langle r \rangle_0$ are the mean n th moments according to the current and initial distribution functions and the mean linear size according to the initial distribution function;

for a kinetic mode ($K \ll \alpha_d$)

$$f_0(r) = a \exp(-ar); \quad a = \frac{1}{\langle r \rangle_0};$$

$$\langle r^n \rangle = \langle r^n \rangle_0 = \langle r \rangle_0^n \Gamma(n+1). \quad (5)$$

From expressions (2)–(5) we can determine the fuel particle burnout ratio y for different modes; in addition, these expressions correlate the mean current moments with the mean initial moments and the mean initial linear size of particles. Hence, if we wish to solve problems concerned with combustion of polydispersed particles, it is sufficient to know their mean initial linear size.

Now, we write the equation for the relative fuel particle burnout rate in the diffusion and kinetic modes (denoted by the subscripts “d” and “k”) according to (2)–(5):

$$\left(\frac{dy}{d\tau}\right)_d = -\frac{2\Gamma^2(3/2)\beta C_k D_0}{\langle r \rangle_0^2 \rho_p} \left(\frac{T_g}{273}\right)^{m-1} y;$$

$$\left(\frac{dy}{d\tau}\right)_k = -\frac{\beta C_{ox} k_0}{\langle r \rangle_0 \rho_p} \left(\frac{273}{T_g}\right) \exp\left(-\frac{E}{RT_p}\right) y.$$

We can confine the analysis by consideration of a limiting mode only in certain cases, but generally, the kinetic and diffusion factors must be taken into account simultaneously. For convenience, we will use the notion of mode criterion [1] characterizing the correlation between the kinetic and diffusion components ($0 < R_k < 1$):

$$R_k = \frac{1}{1 + \left(\frac{dy}{d\tau}\right)_d / \left(\frac{dy}{d\tau}\right)_k}. \quad (6)$$

Despite the fact that the relative combustion rates were obtained for the limiting modes (the diffusion and kinetic ones), we will combine them into a single expression for an intermediate mode, which is similar to Eq. (3) for the combustion rate of an individual particle. Then we have

$$\frac{dy}{d\tau} = \frac{1}{\frac{1}{\left(\frac{dy}{d\tau}\right)_k} + \frac{1}{\left(\frac{dy}{d\tau}\right)_d}} = \left(\frac{dy}{d\tau}\right)_d R_k. \quad (7)$$

In [6], the problem of calculating the burnout of polydispersed pulverized coke was solved taking heat transfer into account. It was assumed that initially, pulverized fuel is blown into the volume of gases (air) heated to a high temperature sufficient for igniting the fuel. But the ignition process itself was omitted completely, which, despite taking a relatively short period of time with respect to the whole burnout process, plays the determining role, a circumstance that was pointed out by many researchers, e.g. [1–3].

In reality, particles are heated to the ignition temperature by means of radiant transfer of heat from bodies having a higher temperature and by convective

heat transfer owing to recirculating part of combustion products from the flame core to the orifice of burners, with convection accounting for the major part of the heat being transferred. These combustion products have certain average temperature of the zone from which they recirculate. Moreover, this temperature may vary as the recirculation gases move toward the burner orifices due to the fact that they may contain unburned fuel particles and oxidizer. As these gases are mixed with the main flow, a mixture of pulverized fuel, air, and combustion products is formed, which has certain average values of temperature and oxidizer concentration. An increase of temperature and a decrease of oxidizer concentration in the produced mixture have an opposite effect on the fuel burnout rate. It is necessary to find the optimal ratio of these parameters for different characteristics of pulverized fuel and combustion conditions. The recirculation ratio, which is determined by the burner design and flow-out conditions, may turn to be insufficient for heating the mixture to the ignition temperature in mixing the fuel with the total amount of air supplied for combustion (our calculations confirm this statement). Thus, a need arises to divide the air supplied for combustion into primary air supplied together with pulverized fuel and secondary air, which is gradually admixed to the ignited mixture [3]. These specific features are taken into account in constructing the proposed combustion model.

The variety of coals and essential differences between their properties, which have an effect on the specific features pertinent to their combustion, are due to different compositions of coals. Apart from carbon, ash, volatiles, and moisture may form a considerable fraction. Despite the fact that the combustion of coke residue determines the main time taken for particles to burn out, it is still insufficient to use only the model of coke particles combustion for natural solid fuel.

The following assumptions are taken in constructing the model:

- (i) Natural fuel having a certain composition is considered.
- (ii) The reaction proceeds on the surface of spherically shaped particles.
- (iii) Particles are not destructed during the reaction.
- (iv) The combustion process goes according to the primary reaction with formation of carbon dioxide.
- (v) Particles residing in gaseous medium are at rest or move with it without slipping of phases.
- (vi) Heat transfer between particles and gaseous medium takes place by convection and radiation.
- (vii) The substances are assumed to be ideally mixed.
- (viii) The combustion process is assumed to be quasi stationary and self-similar in nature.

(ix) Ash is completely separated from ash-free particles as a result of milling and has the temperature of carrying gases.

(x) The temperature of admixed secondary air remains unchanged, and the temperature of volatiles is equal to the temperature of gases.

(xi) There are no air inleakages in the furnace.

(xii) The fuel does not react in the flow of recirculation gases.

(xiii) The presence of water vapor can be neglected.

(xiv) Heat transfer with ash particles is not considered.

Since such a model does not take into account the flow hydrodynamics and specific features pertinent to the release of volatiles, the variations of recirculation gases and secondary air flowrates with respect to the main flow, as well as volatile release and combustion processes are specified by functions describing the available experimental data.

The heat balance equations for particles and gas are given by

$$G_p c_p dT_p = -Q_k dG_p - \alpha_p (T_p - T_g) dF_p - \varepsilon_{p-g} \sigma_0 (T_p^4 - T_g^4) dF_p - \varepsilon_{p-w} \sigma_0 (T_p^4 - T_w^4) dF_p; \quad (8)$$

$$(G_f c_f + G_{c,p} c_{c,p} + G_v c_v + G_{ash} c_{ash}) dT_g = -Q_v dG_v + \alpha_p (T_p - T_g) dF_p + \varepsilon_{p-g} \sigma_0 (T_p^4 - T_g^4) dF_p - \alpha_g (T_g - T_w) dF_w - \varepsilon_{g-w} \sigma_0 (T_g^4 - T_w^4) dF_w - c_f (T_g - T_{f2}) dG_{f2} + c_{c,p} (T_p - T_g) dG_{r,c,p} + c_f (T_p - T_g) dG_{r,a}, \quad (9)$$

where G_p , G_a , $G_{c,p}$, G_{ash} , and G_v are the current mass flowrates of coke particles, air, combustion products, ash, and volatiles in the considered flow; $G_{r,c,p}$, $G_{r,a}$, and G_{a2} are current mass flowrates of combustion products and air forming the recirculation gases, and of secondary air admixed to the main flow; c_p , c_a , $c_{c,p}$, c_{ash} , and c_v are the average (in the considered temperature ranges) specific heat capacities of fuel, air, combustion products, ash, and volatiles; Q_c and Q_v are the heating values of ash-free coke and volatiles; α_g and α_p are the coefficients of convective heat transfer from gases to the furnace walls and between particles and gases; F_w and F_p are the surface areas of walls and particles (current); T_w , T_{a2} , and T_r are the temperatures of furnace walls, secondary air, and recirculation gases; $\varepsilon_{p,g}$, $\varepsilon_{p,w}$, and $\varepsilon_{g,w}$ are the reduced radiation capacities of the "particles-gas," "particles-walls," and "gas-walls" systems; and σ_0 is the emissivity of a black body.

The mass flowrates of particles, air, and generated combustion products, ash, and volatiles are propor-

tional to the fuel flowrate G_0 . Thus, the following relations are valid for fuel particles, ash, and volatiles:

$$G_p = G_{p0}y = G_0(1 - W^r - A^r)(1 - V^{c.m})y;$$

$$G_{ash} = G_0A^r;$$

$$G_v = G_{v0}m_v(\tau) = G_0(1 - W^r - A^r)V^{c.m}m_v(\tau),$$

where A^r and W^r are the contents of ash and moisture in the fuel per working mass, $V^{c.m}$ is the yield of volatiles per combustible mass, G_{v0} and G_{p0} are the initial mass flowrates of volatiles (conditionally) and particles, and $m_v(\tau)$ is the specified function describing the variation with time of the fractions of volatiles in the main flow with respect to their maximal values.

Calculation of the mass flowrates of air and combustion products is a more difficult task, because their values are determined by the combustion processes and secondary air and recirculation gases supply processes:

$$G_a = G_0V_a^0\rho_a[\alpha_1 + \alpha_2m_{a2}(\tau) - 1 + y(1 - V^{c.m}) + m_v(\tau)V^{c.m} + b\alpha_r m_r(\tau)];$$

$$G_{c.p} = G_0\rho_{c.p}\left[V_{c.m}^0(1 - y(1 - V^{c.m}) - m_v(\tau)V^{c.m}) + (1 - b)\alpha_r m_r(\tau)V_a^0\right],$$

where $V_{c.m}^0$, V_a^0 are the theoretical volumes of combustion products and air required for combustion; ρ_a and $\rho_{c.p}$ are the densities of air and combustion products at standard temperature and pressure; α_1 , α_2 , α are the primary, secondary and total air excess factors in the furnace; r_r is the gas recirculation ratio with respect to the entire air supplied for combustion; b is the volume fraction of residual air in recirculation gases; and $m_{a2}(\tau)$, $m_r(\tau)$ are the specified functions describing the variation with time of the fractions of secondary air and recirculation gases in the main flow with respect to their maximal values.

If there is no phase slipping (particles and gases), the Nusselt number is equal to 2. Then, the convective coefficient of heat transfer from particles to gases is determined as $\alpha_p = \frac{\lambda_{c.m}}{\langle r \rangle_0}$, where

$\lambda_{c.m} = \lambda_{c.m0}(T_{c.m}/273)^{0.8}$ is the heat conductivity coefficient of gases, and $\lambda_{c.m0}$ is the heat conductivity coefficient of gases at standard temperature and pressure.

The current surface area of coke particles F_p can be obtained as $F_p = F_{p0}y$, where F_{p0} is the initial surface area of particles calculated from the initial distribution function $f_0(r)$. Then, the specific surface area F_p/M_{p0} can be determined for the diffusion and kinetic modes on the basis of (4) and (5) as follows:

$$\left(\frac{F_p}{M_{p0}}\right)_d = \frac{2}{\rho_p \langle r \rangle_0} y; \quad \left(\frac{F_p}{M_{p0}}\right)_k = \frac{1}{\rho_p \langle r \rangle_0} y.$$

Using the notion of mode criterion (6), we obtain for an intermediate mode

$$\frac{F_p}{M_{p0}} = \frac{1}{\rho_p \langle r \rangle_0} [(1 - R_k) + 2R_k] y = \frac{R_k + 1}{\rho_p \langle r \rangle_0} y.$$

The presented radiation capacities ε_{p-g} , ε_{p-w} , and ε_{g-w} are determined for particular conditions of firing polydispersed fuel because they also depend on the fuel burnout ratio [7] and can be taken constant only after the major mass of fuel has burnt out. Therefore, their averaged values are taken in the subsequent calculations.

The heating value of volatiles is calculated from the formula

$$Q_v = \frac{1}{V^{c.m}} \left[\frac{Q^r}{1 - W^r - A^r} - Q_k(1 - V^{c.m}) \right],$$

where Q^r is the fuel heating value per working mass.

In such statement of the problem, by solving the system of Eqs. (7)–(9) taking all additions into account we can determine the change with time in the fuel burnout ratio and rate, temperatures of particles and gas, and other quantities depending on the parameters mentioned above.

The problem was solved for the conditions of firing pulverized Donetsk anthracite culm in the furnace of a TP-70 boiler [8]. Since an insufficiently complete description of experimental conditions and results was available, the values of some quantities in the calculation could be selected incorrectly. We took as initial conditions the temperatures of particles, gases (primary air), and secondary air $T_{p0} = T_{g0} = T_{a2} = 573$ K, of recirculation gases $T_r = 1850$ K, the average initial radius of particles $\langle r \rangle_0 = 30$ μm , and the fraction of residual air in recirculation gases $b = 0.3$. The obtained solution must provide the initial conditions connected with recirculation.

According to the experimental data of [8], the major mass of gases recirculating from the flame core to the burner orifices is admitted in the axial zone. The mass flowrate of recirculation gases in the main flow varies over the jet length, first increasing from zero to the maximal value and then again decreasing to zero. The supply of secondary air is also nonuniform over the jet length because it is gradually mixed with the main flow. The mass flowrate of admixed secondary air increases from zero to the maximal value with decreasing intensity of mixing. On reaching the ignition point, the volatiles releasing in the course of particle heating process burn out rapidly.

In a first approximation, the functions describing the change of fractions of volatiles $m_v(\tau)$, secondary air $m_{a2}(\tau)$, and recirculation gases $m_r(\tau)$ in the main flow

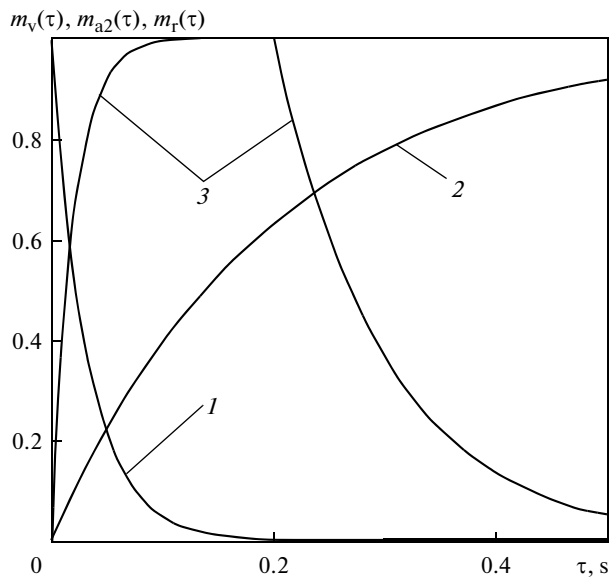


Fig. 1. Form of functions adopted in the calculations. (1) $m_v(\tau)$, (2) $m_{a2}(\tau)$, and (3) $m_r(\tau)$.

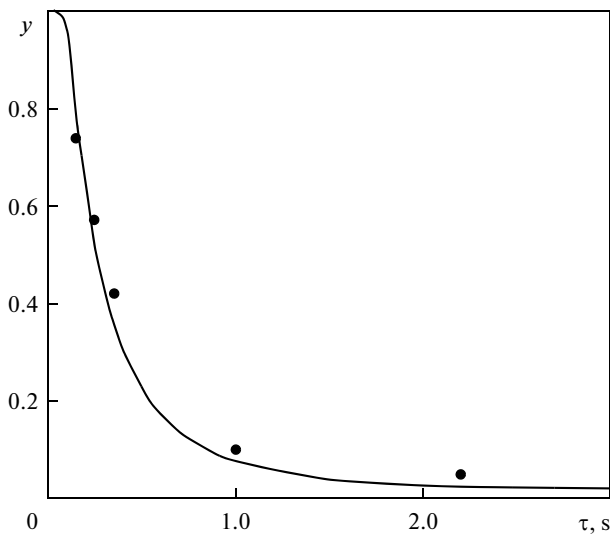


Fig. 3. Calculated time dependence of the fuel particle burn-out ratio. Points represent the experimental data of [8].

can be represented by the following exponential dependences (Fig. 1):

$$m_r(\tau) = \begin{cases} 1 - \exp(-50\tau) & \text{at } \tau < 0.2; \\ \exp[-10(\tau - 0.2)] & \text{at } \tau \geq 0.2; \end{cases}$$

$$m_v(\tau) = \exp(-30\tau); \quad m_{a2}(\tau) = 1 - \exp(-5\tau).$$

The results of calculations are presented in Figs. 2 and 3. An analysis of the obtained data shows the following:

(i) The calculated curves are in fairly good agreement with the experimental data.

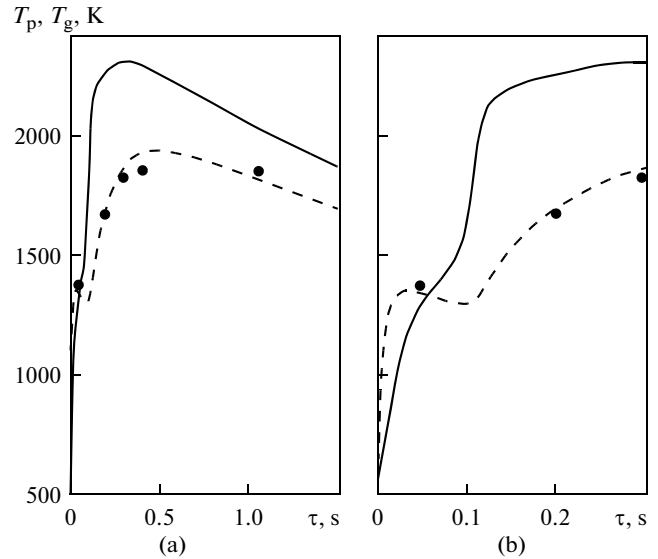


Fig. 2. Calculated time dependences of the temperatures of particles (solid curves) and gases (dashed curves). Points represent the experimental data of [8] on gas temperature. (a) From 0 to 1.5 s and (b) from 0 to 0.3 s.

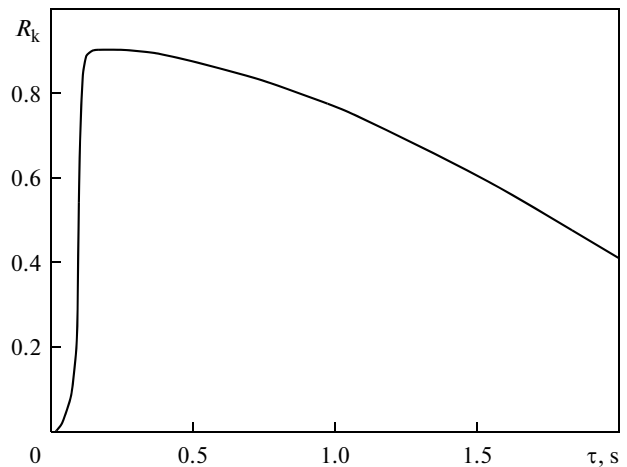


Fig. 4. Variation with time of the mode criterion.

(ii) The mixture is heated to the coke particle ignition temperature within a short period of time due to intense heat transfer between particles and gas (predominantly by convection). This heating process is characterized by almost complete absence of coke burnout, which is confirmed by calculations of ignition and combustion of a monodispersed system of particles [3].

(iii) The difference between the temperatures of particles and gases reaches high values (up to 730 K).

(iv) The major mass of fuel burns out after its ignition within a short interval of time.

The found values of temperatures allow us to determine the predominant burnout mode for the considered fuel particles. Figure 4 shows the change with time of the mode criterion.

A comparison of Figs. 2–4 shows that fuel is ignited in a kinetic mode. The value of R_k becomes greater than 0.5 only after particles have partially burnt out heated to 1720 K (at a gas temperature of 1300 K), which points to predominance of diffusion factors. Since the value of R_k varies in fact from 0 to 0.9, an analysis performed with disregarding one combustion mode or another would yield an essentially incorrect result.

CONCLUSIONS

(1) The presented model for combustion of natural polydisperse fuel provides a fairly complete description of heating, ignition, and burnout processes taking into account heat transfer with the surfaces enclosing the combustion chamber volume, fuel composition, and specific features of operating parameters.

(2) By using the proposed approach, it becomes possible to essentially reduce the amount of calculations required for analyzing the burnout of polydisperse solid fuel as compared with the fraction-wise method.

(3) The use of the developed model makes it possible to estimate the influence of different parameters (average size of particles, initial air temperature, reaction rate constant, etc.) on the ignition of fuel particles and their burnout under the conditions of external heat transfer.

(4) The proposed method of taking into account the recirculation of hot combustion products, release and combustion of volatiles, and supply of secondary air is a first approximation and needs refinement. If we wish to determine, e.g., the functions describing variation of recirculation and secondary air flows, addi-

tional experimental data are required that would allow these functions to be obtained for different types of used burners.

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