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STUDY OF TRAJECTORIES AND COMBUSTION OF FUEL-OIL DROPLETS  
IN THE COMBUSTION CHAMBER OF A POWER-PLANT BOILER WITH THE USE  
OF A MATHEMATICAL MODEL

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A mathematical model is developed to permit study of the behavior of fuel-oil droplets in a combustion chamber, and results are presented from a computer calculation performed for the 300-MW model TGMP-314P boiler of a power plant.

A mathematical model has been developed for power-plant boilers having burners installed vertically on the hearth of the combustion chamber. This arrangement was chosen due to the simplicity of the aerodynamics of such a combustion chamber and the possibility of performing a detailed empirical check of the calculated results.

In contrast to completely vaporized liquid fuel, fuel oil burns with the formation of a solid phase. The complete combustion of this phase is subject to the laws of heterogeneous chemical reactions and proceeds at a rate considerably below the rate of complete combustion of liquid-fuel vapors. Complete combustion of the solid phase is one of the main limiting factors in the combustion process and ultimately determines the length of the fuel-oil flame.

Studies conducted by the All-Union Institute of Heat and Power Engineering have shown that the coke residues of unburned fuel-oil droplets consist mainly of hollow spherical particles containing one coarse hole. The solid particles are spherical mainly because of the formation of a coke shell on their surface during combustion and vaporization of the droplet, the rupture of this shell being accompanied by the ejection of some of the vapors and liquid therein. Studies of the combustion of single droplets of fuel oil have shown that the diameter of the coke residue is usually 0.5-0.7 of the initial diameter of the drop [1]. According to our data, its inside diameter is approximately  $0.3d_{p0}$ .

The program written to perform the calculations was organized so that the first stage would entail calculation of the combustion (vaporization) of a droplet of liquid fuel to a diameter corresponding to 0.6 of the initial droplet size  $d_{p0}$ . The program then provided for a sudden decrease in the mass of the fuel particle, simulating rupture of the coke shell and ejection of some of the liquid. The program then considered the combustion of a hollow coke particle with an outside diameter of  $0.6d_{p0}$  and an inside diameter of  $0.3d_{p0}$ . In accordance with this plan, physicochemical parameters characteristic of fuel oil M-100 were introduced in the program in the first stage of computations, while parameters characteristic of the coke particle associated with an unburned fuel-oil droplet were included in the second stage.

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A similar approach was used to solve a fuel-oil combustion problem in [2] and seems to us to be the most promising method of investigation.

The computation was based on numerical machine integration of the equations of motion and combustion first of the liquid fuel droplet and then of the coke residue of the droplet.

We attempted to use the following simplified model of the process. A single fuel particle of the diameter  $d_p$  is fed into a gas flow leaving the nozzle of a burner installed on the axis of the combustion chamber. The particle has an initial velocity  $v_0$  and moves at an angle  $\beta$  to the y-axis. Since most of the air (more than 80%) leaving the hearth burners is moving in nearly a straight line and since the fuel-air mixture is flowing symmetrically relative to the burner axis, we can reduce the problem to two dimensions and solve it in cartesian coordinates.

The motion of the fuel particle under the influence of inertial, aerodynamic, and gravitational forces is described by the equations

$$m_p \frac{dv_{px}}{d\tau} = C_a \psi \frac{(u_x - v_{px}) v_{rel} \gamma_g F_p}{2g} - m_p g,$$

$$m_p \frac{dv_{py}}{d\tau} = C_a \psi \frac{(u_y - v_{py}) v_{rel} \gamma_g F_p}{2g}.$$

The drag coefficient of the liquid fuel droplet was assumed to be equal to the drag coefficient of a spherical particle, with allowance for a correction for its enlargement due to its distortion by aerodynamic forces. This correction was obtained in the form of the following relation from S. A. Belyi's analysis of experimental data produced by K. I. Svetushkin

$$\psi = \exp(0,03D_q^{1,5}),$$

where

$$D_q = \gamma_g v_{rel}^2 d_p / \sigma_p$$

The drag coefficient of the spherical particle was found from generalized experimental data given in the form of the relation

$$C_a = f(\text{Re} = v_{rel} d_p / \nu).$$

The relative velocity of the particle was calculated as the difference of the vectors  $\bar{u}$  and  $\bar{v}_p$  from the formula

$$v_{rel} = \sqrt{(u_x - v_{px})^2 + (u_y - v_{py})^2}.$$

In calculating the combustion of the coke particle, we calculated the drag coefficient from the empirical relation obtained by V. I. Babii and I. P. Ivanova [3]:

$$C_a = \frac{52}{\text{Re}} \left( \frac{T_p}{T_g} \right)^{1,7}.$$

Here, the temperature of the burning particle was determined from the formula

$$T_p = T_g + 0,033(2010 - T_g) d_p^{-0,16} O_2,$$

where  $O_2$  is the concentration of oxygen in the volume surrounding the particle.

The temperature of the burning fuel-oil flame changes within a relatively narrow range (2000-1600°K) over the height of the combustion chamber of power-plant boilers.

The temperature distribution over the height of the combustion chamber can be prescribed either from the results of experimental studies of boiler-analogs or from combustion models. It can also be calculated by the method in [4].

The axial and radial components of the velocity of the gas flow in the combustion chamber can be obtained from data from aerodynamic studies of models of combustion chambers, with appropriate corrections for the nonisothermal character of the process. The temperature and velocity distributions were introduced into the mathematical model in the form of a detailed grid of values over the height of the combustion chamber.

The combustion of the liquid phase was calculated in accordance with the diffusion theory of G. A. Varshavskii. The change in the diameter of the droplet due to vaporization (combustion) was determined from the formula derived by B. I. Sreznevskii:

$$d_{pr}^2 = d_{p0}^2 - \kappa\tau.$$

The vaporization (combustion) constant was calculated by the method proposed in [5]:

$$\kappa = \frac{4Nu k_\lambda}{\gamma_f k_c} \left\{ \frac{1}{2} \ln \left[ 1 + \frac{k_c T_2 (T_2 - T_1)}{H} \right] + \frac{1}{\vartheta} \left( \operatorname{arctg} \frac{2 \frac{T_2}{T_1} - 1}{\vartheta} - \operatorname{arctg} \frac{1}{\vartheta} \right) \right\},$$

where  $\vartheta$  is a dimensionless quantity equal to  $\sqrt{\frac{4H}{k_c T_1^2} - 1}$ .

Experimental verification of the diffusion theory by different investigators has shown that it is qualitatively correct. When the droplet is surrounded by a region in which its vapors are undergoing combustion, the theoretical results agree quantitatively with experimental findings only if the adiabatic stoichiometric combustion temperature is taken as the theoretical temperature of the combustion region. The adiabatic stoichiometric combustion temperature is calculated from the formula

$$T_2 = \frac{Q_1^w + c_f t_f + V_a^0 c_a t_g}{c_g V_g^0} + 273.$$

The Nusselt criterion for calculations of the combustion of liquid fuel was determined from the empirical formula obtained by Rains and Marshall:

$$Nu = 2 + Pr^{0.8} Re^{0.5}.$$

The combustion of the coke residue was calculated in accordance with the theory of combustion of solid fuel particles [6].

Using the notion of the specific rate of carbon combustion  $K_s^C$  introduced by L. N. Khitrin, we can write the differential material-balance equation for a spherical coke particle in the form

$$d \left( \gamma_p \frac{\pi d_p^3}{6} \right) = - K_s^C \pi d_p^2 d\tau. \quad (1)$$

After transformation of Eq. (1), we obtain

$$\frac{dd_p}{d\tau} = - \frac{2K_s^C}{\gamma_p}. \quad (2)$$

The detailed theoretical analysis of the combustion of a single particle performed in [6] showed that the following expression can be used for  $K_s^C$  in calculations of combustion rate:

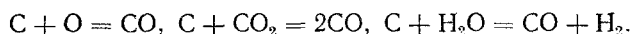
$$K_s^C = \beta_c \frac{C}{\frac{1}{\alpha_k} + \frac{1}{\frac{D}{d_p} Nu_{dif}}}.$$

Most engineering methods of calculating carbon combustion in fuel-burning devices have been developed only with regard for the primary heterogeneous reactions involving the combination of carbon with oxygen. This simplifying assumption is justified to some extent for pulverized-coal furnaces, with allowance for the fairly large excess of air and, thus, the high oxygen concentration at which solid fuel combustion occurs. Calculation of the combustion of a fuel-oil jet requires consideration of secondary heterogeneous reactions between carbon on the one hand and carbon dioxide and water vapor on the other hand. This is due to the following factors. Coke particles associated with the droplets of fuel oil are burned in the tail part of the jet — where oxygen concentration is low because most of the oxygen has already been used in complete combustion of vapors of the liquid phase. Also, fuel-oil boilers

operate with considerably smaller excesses of air than do pulverized-coal boilers. At the end of the combustion chamber, fuel-oil boilers — operating with limitingly small excesses of air — have an oxygen content lower than 1 vol. % in the flue gases. Here, the CO<sub>2</sub> content is more than 15 vol. %. Given these conditions, despite the fact that the order of the reactions involving carbon-oxygen combination is higher than the order of reactions involving the combination of carbon and carbon dioxide, the loss of carbon mass in the latter reactions becomes comparable to the loss in the primary heterogeneous reaction. It is even sometimes greater, due to the appreciably higher concentration of carbon dioxide present.

The need to account for the reaction of carbon with water vapor is dictated first by the fairly large amount of such vapor in fuel-oil combustion chambers, due to the fact that the burning fuel oil contains about 12% hydrogen. Also, water vapor enters the chamber as an atomizing agent from the nozzles, and the fuel oil comes into contact with water during its transport and discharge from the tank car. The second reason to account for the reaction of carbon with water vapor is the high pyrometric level in modern oil furnaces (1700-2000°K). In our calculations,  $K_S^C$  was calculated as the sum of the specific rates of combustion in three combination reactions involving carbon — with oxygen, carbon dioxide, and water vapor. The mass concentrations of O<sub>2</sub>, CO<sub>2</sub>, and H<sub>2</sub>O during combustion of the coke particles were calculated from material balance formulas for the reactants. These formulas are omitted here due to their awkwardness.

The stoichiometric factor  $\beta_C$  was determined as the purely chemical stoichiometric coefficient for the reactions



The coefficient of molecular diffusion D and the diffusion analog of the Nusselt criterion were calculated from experimental data [7], which was generalized by the respective relations:

$$D = 0,16 \cdot 10^{-4} \left( \frac{T_g}{273} \right)^{1,9},$$

$$Nu_{\text{dif}} = 2 + 0,17 Re^{0,66}.$$

The coefficient characterizing the rate of the chemical reaction was found from the Arrhenius equation:

$$\alpha_k = K_0 \exp \left( - \frac{E}{RT_p} \right).$$

The quantities  $K_0$  and E were taken from experimental data in [8] for the reaction of carbon with oxygen. This data was obtained for petroleum coke. The values of the same quantities for the reactions of carbon with carbon dioxide and water vapor were taken from the experimental data in [9].

Until recently, when carbon combustion in a hot flame was calculated, it was usually assumed that the reaction surface was equal to the external surface of the particle.

The imbalance in the calculations was often compensated for by an arbitrarily chosen particle form factor.

It was assumed on the basis of diffusion-kinetic theory that the depth of the reaction zone should decrease with an increase in temperature, mainly due to an exponential increase in the rate constant of the chemical reaction. The reaction was assumed to be localized on the outside surface. This assumption has been refuted in recent years by experiments involving the study of internal reactions at high temperatures. M. S. Orenbach [10] showed experimentally that the percentage of the internal reaction taking place in the combustion of coke residues of particles of brown coal may reach 55% in the heating of a dust suspension in inert and oxidizing media above 1600°C. The same investigator suggested that the development of a macroscopic pore space inside the coke particles at high temperatures is related to the reaction of the walls of the pores and cracks not with oxygen, but with carbon dioxide. The concentration of the latter is evidently considerably higher than that of the former near the particle surface. Also, since carbon dioxide is a product of the complete combustion of carbon monoxide, it can diffuse into the pores to a greater depth than can oxygen. Experimental studies [9] of the behavior of the pore structure of carbon reacting with CO<sub>2</sub> show that parti-

cles no larger than 500  $\mu\text{m}$  will fully react at high temperatures even when the flow velocities are low, and calculated values of the rate of entrainment of the substance referred only to the outside surface will not correspond to the actual values.

Studies of coke particles associated with unburned fuel-oil droplets taken from a combustion chamber showed that these particles are highly porous structures. The specific surface of coke particles determined by the BET (Brunauer-Emmett-Teller) method ranged from 8 to 13.45  $\text{m}^2/\text{g}$ , depending on the narrow fraction investigated. To evaluate the size of pores in coke particles, we employed the method of mercury porosimetry. Analysis of the integral porograms showed that coke particles in fuel oil are characterized by the presence of a large number of coarse pores larger than 1000  $\text{\AA}$ . The total porosity of the coke particles was 0.5  $\text{cm}^3/\text{g}$ .

When analyzing the possibility of internal reaction of coke particles in fuel oil, it is also necessary to consider that, in contrast to coal coke, fuel-oil coke is nearly ash-free. This allows unobstructed access of the oxidant to the reaction surface of carbon during combustion. Since we are dealing with fairly coarse, highly porous coke particles which burn in an atmosphere with a high concentration of carbon dioxide when we calculate the combustion of a fuel-oil jet, failure to allow for the internal reaction leads to serious errors.

The increase in the rate of combustion of coke particles due to the internal reaction was accounted for in our calculations by following the practice in [9] and introducing the term  $(1 + 0.04S^*)$  in the numerator of the right side of Eq. (2). Here,  $S^*$  is the relative (per unit of external surface) internal surface of the coke particle. It was shown in [9, 11, 12] that the reactivity is not equal to the internal surface of the coke particle determined by the BET method. It is 3-5% less than the latter, in accordance with which we introduced a multiplier of 0.04.

Experimental studies of the specific surface of several narrow fractions of fuel-oil coke particles in the range 25-320  $\mu\text{m}$  showed that the value of  $S^*$  can, with an accuracy sufficient for practical purposes, be calculated from the following empirical relation:  $S^* = 147\sqrt{d_p}/0.000125$ .

Having taken the value of  $K_s^C$  found by the above-described method and having inserted it into Eq. (2), we can use numerical integration to calculate the change in the diameter of the coke particle over the length of the flame:

$$dd_p = - \frac{2K_s^C(1 + 0.04S^*)d\tau}{\gamma_p}$$

The problem was solved on a BESM-6 computer. For variant calculations, we adopted the following ranges of the governing parameters:  $\beta = 15-55^\circ$ ;  $d_{p0} = 100-1000 \mu\text{m}$ ;  $u_0 = 20-60 \text{ m/sec}$ ;  $v_{p0} = 25-80 \text{ m/sec}$ ;  $\alpha_T^H = 1.01-1.4$ .

The results of the calculations show that the trajectories of the fuel particles in the combustion chamber depend mainly on their velocity and the angle of their entry into the chamber, the mass of the particle, and the air velocity at the burner outlet (Fig. 1). As a result of the aggregate effect of forces attributable to the initial energy and angle of discharge of the fuel from the nozzle, the energy of the gas flow, and gravitational forces, coarse fuel particles move toward the periphery of the flame as it grows, while fine particles move closer to the axis of the burner. Coarse particles ( $d_{p0} > 0.6 \text{ mm}$ ) leaving the nozzle at high angles ( $\beta > 40^\circ$ ) do not burn but instead impact against the baffle in the combustion chamber. The flame usually impinges on shields located at these sites in actual boilers, leading to the formation of coke deposits and high-temperature corrosion of the shield tubes.

Some of the coarsest particles are broken up by aerodynamic forces associated with the air flow. In our calculations, the critical relative velocity at which secondary breakup of the fuel droplets takes place was evaluated by the method devised by M. S. Volynskii [13]. The degree of secondary refinement of the liquid droplets depends on a whole range of factors, but the decisive role here is played by the air velocity at the burner outlet and the angle of taper of the fuel spray from the nozzle. The greater these quantities, the higher the relative velocities of the phases which can be attained. A similar but lesser role is played by the velocity of the fuel at the nozzle outlet.

Calculations show that for the most characteristic air velocities at the burner outlet — on the order of 50-60  $\text{m/sec}$  — and with the most characteristic angles of taper corresponding to the spray-density maximum on modern pressure steam burners — on the order of  $35^\circ$  — most droplets larger than 700  $\mu\text{m}$  are broken up at the edge of the burner port.

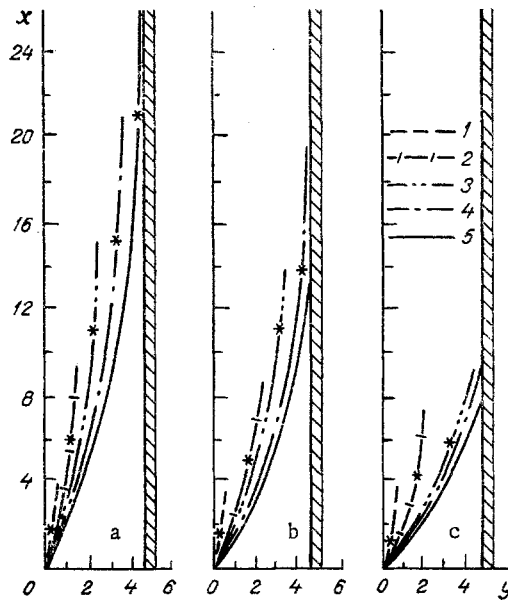


Fig. 1. Trajectories of fuel particles in a combustion chamber ( $u_0 = 50$  m/sec;  $v_{p0} = 80$  m/sec;  $\alpha_T'' = 1.02$ ): 1)  $d_{p0} = 200$   $\mu$ m; 2) 400; 3) 600; 4) 8000; 5) 1000; \*) site of termination of liquid-phase combustion; a)  $\beta = 25^\circ$ ; b) 35; c) 45.  $x, y, m$ .

An evaluation of the configuration and length of the flame conducted for the combustion of the coarsest particles — which cannot be broken up by the aerodynamic forces of the air flow — showed that the calculated results agree well with the results of experimental studies on an actual model TGMP-314P boiler [14].

According to data from theoretical studies, the decisive effect on the combustion of fuel-oil droplets is exerted by the diameter of the fuel particles and their residence time in the combustion chamber. A reduction in fuel particle size can be achieved both by using more modern means of dispersing the liquid fuel and by creating conditions which are favorable for efficient secondary refinement of the fuel droplets at the edge of the burner port.

In calculations of the combustion of a spray of organic fuel, it is customary to determine the particle residence time in the reaction zone from the mean-flow-rate velocity of the gases referred to the cross-section of the combustion chamber [2].

Our theoretical studies showed that for combustion chambers in which the burners are located in the hearth, the fuel-particle residence time in the chamber is considerably shorter, and failure to allow for this may lead to sizable errors. For example, for the most characteristic air velocities at the outlet of the burner — on the order of 50–60 m/sec — and with the use of pressure steam burners operating under the nominal load at a fuel-oil pressure of 35 kg/cm<sup>2</sup> ( $v_{p0} \approx 80$  m/sec), the theoretical residence time (in the combustion chamber) of fuel particles with a diameter equal to the mean median droplet size is no more than 0.7–0.8 sec for a TGMP-314P boiler. This is roughly one-third the time calculated from the mean-flow-rate velocity of the gases in the combustion chamber.

The air velocity at the burner outlet affects fuel combustion in two ways. On the one hand, an increase in air velocity leads to an increase in the degree of secondary refinement of the fuel drops and a corresponding shortening of the flame due to a reduction in the critical droplet size. Also, an increase in air velocity increases the relative velocities of the phases — particularly on the initial section of the flame. This also leads to an increase in the fuel combustion rate due to an increase in the Nusselt criterion.

On the other hand — and this applies particularly to combustion chambers with burners located in the hearth — an increase in air velocity at the burner outlet significantly shortens the particle residence time in the combustion chamber. The last factor is the predominant factor for the hearth-burner scheme. For other schemes, such as combustion chambers with opposing burners, the first-mentioned factors have the greatest effect on flame length with a change in air velocity in the burners.

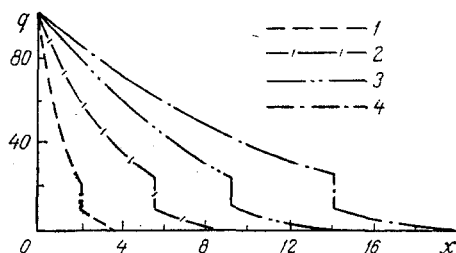


Fig. 2. Combustion of fuel particles over the height of a combustion chamber ( $u_0 = 50$  m/sec;  $v_{p0} = 80$  m/sec;  $\alpha_T'' = 1.02$ ;  $\beta = 35^\circ$ ): 1)  $d_p^0 = 200$   $\mu\text{m}$ ; 2) 400; 3) 600; 4) 800.  $q$ , %.

Experimental studies show that the effect of the excess air coefficient is manifest most strongly in the combustion of the vapor phase of liquid fuel and the components associated with chemical underfiring. The rate of combustion of the coke residue of fuel-oil droplets depends to a lesser extent on the excess air, since secondary heterogeneous reactions of carbon with carbon dioxide and water vapor begin to exert a greater effect on carbon loss in the end sections of the flame.

Calculations show that the rate of combustion of the coke residue is approximately 8-10 times lower than the rate of combustion (vaporization) of the liquid phase (Fig. 2). About 40-45% of the lifetime of a fuel-oil particle is spent in combustion of the coke residue, with about 7% of the heat ( $q$ ) corresponding to this component (Fig. 2).

The above-described method does not consider several factors which have a significant effect on the indices of the combustion process in the boiler — the uniformity of fuel and air distribution among the burners, design features of the burners, the effect of turbulence, etc.

In evaluating the length of the flame, we also failed to consider that finely dispersed soot is formed along with coke particles during combustion in zones with a reducing medium due to the pyrolysis of petroleum vapors and components associated with chemical underfiring ( $\text{CO}$ ,  $\text{CH}_4$ ). Although our data suggests that the percentage of pyrolytic soot is usually no greater than 10-15% of the weight of the unburned coke particles, it may have a significant effect on the final results in regimes with limitingly low excesses of air and, especially, with a non-uniform fuel and air distribution among the burners.

Nevertheless, the method for calculating the trajectories and combustion of fuel-oil droplets which was developed here makes it possible to determine the conditions for the development of the flame in a combustion chamber, reveal the sites where the flame contacts with the shields in the chamber, calculate the dynamics of fuel combustion over the chamber height, and evaluate the effect of the governing regime and design parameters on the basic indices of the combustion process.

All of these characteristics make it possible to offer several practical recommendations on the power, number, and placement of burners in a combustion chamber, to evaluate the configurations which are most dangerous in regard to the likelihood of high-temperature gas corrosion, and to predict the location of regions in which heat release from the flame will be maximal.

#### NOTATION

$d_{p0}$ , initial diameter of fuel-oil droplets;  $d_p$ , running diameter of fuel particle;  $v_p$ , velocity of fuel particle;  $\beta$ , angle between the axial velocity vector of the particle and the y-axis;  $C_a$ , particle drag coefficient;  $\psi$ , coefficient accounting for the increase in droplet drag due to its deformation by aerodynamic forces;  $u_0$ ,  $u_x$ ,  $u_y$ , mean-flow rate, axial, and radial components of gas-flow velocity;  $v_{px}$ ,  $v_{py}$ , axial and radial components of particle velocity;  $g$ , acceleration due to gravity;  $\gamma_g$ , specific weight of gas;  $\gamma_p$ , specific weight of particle;  $F_p$ , cross-sectional area of particle;  $\sigma_p$ , surface tension of fuel oil at the boiling point;  $v_{rel}$ , relative particle velocity;  $\nu$ , kinematic viscosity of gas;  $T_g$ , gas temperature;  $T_p$ , temperature of burning coke particle;  $\tau$ , time;  $Q_L^w$ , lowest calorific value of fuel per unit mass;  $c_f$ ,  $c_a$ ,  $c_g$ , heat capacity of the fuel oil, air, and flue gases, respectively;  $V_a^0$ ,  $V_g^0$ , theoretical volumes of air and flue gases;  $T_1$ , fuel-oil boiling point;  $H$ , total heat of combustion;  $k_\lambda$ ,  $k_c$ , proportionality factors used in calculating the thermal conductivity of

the gases and the heat capacity of the fuel-oil vapors in relation to temperature;  $C$ , concentration of the gaseous reactant;  $\beta_C$ , stoichiometric factor;  $K_C$ , specific heat of combustion;  $E$ , activation energy;  $K_0$ , preexponential multiplier;  $R$ , gas constant;  $\alpha_T^H$ , coefficient of excess air at the combustion-chamber outlet;  $D$ , coefficient of molecular diffusion;  $\alpha_k$ , coefficient characterizing the rate of chemical reaction;  $S^*$ , relative internal surface of particle;  $Re$ ,  $Pr$ ,  $Nu_{dif}$ , Reynolds, Prandtl, and Nusselt numbers;  $m_p$ , mass of particle;  $D_q$ , criterion of deformation of fluid particle;  $q$ , percentage of unburned fuel (according to heat);  $\kappa$ , fuel-oil particle vaporization (combustion) constant.

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