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MODELLING THE COMBUSTION OF HIGH-ASH CONTENT SOLID FUEL IN CIRCULATING SYSTEMS

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UDC 662.61

We analyze the complete combustion of high-ash content fuel in circulating systems, based on the solution of the equation for the probability density distribution of particles by size and carbon content.

The concept of the creation of ecologically clean methods of processing solid fuels has forced a reconsideration of the merits of traditional torch and bed methods of combustion. It has brought about the first plan for a system with multiple cycling of fuel and ash through external cyclones: furnaces with circulating fluidized or air-charged beds [1-4]. However, despite the significant practical achievements in creating furnaces with circulating fluidized (or air-charged) beds, methods for calculating such devices have only just begun to be developed [5-11]. Naturally, therefore, further progress in realizing circulating systems of solid fuel combustion is linked to the development of methods to mathematically model the relevant processes in these systems. In this work, we analyze certain models of the complete combustion of high-ash content fuel as applied to furnaces with external loop circulation of solid material.

1. To develop the theory for calculating circulating combustion systems, it is necessary to determine the character of the behavior of the ash in the process of complete fuel combustion. Depending on this character, one of the models of carbon particle structure is adopted. In the simplest case, it is assumed that there is complete separation of the ash from the solid carbon in fuel processing devices, which is called the "external ash" model. In this model, the ash has virtually no effect on coke combustion, and calculation of the fractional state of the fuel, number of circulation repetitions and other characteristics of the circulating system reduce to solving the equation for the density distribution by size of the carbon particles and the ash [10]. The "segregated ash" model which circulates in the literature essentially leads to the same computational scheme as that for the carbon particles. Within the framework of this model, it is assumed that the ash is separated and falls out of the particles in the process of combustion. As a rule, this model is valid for low-ash content fuels. For calculating the combustion of high-ash content fuels, the "contracting fuel nucleus" ("progressive ash sheath") and the "volumetric reaction" models have gained wide currency. When using the first of these, it is assumed that diffusion resistance to the transport of oxidizer inside the unburned nucleus is infinitely large, and the heterogeneous chemical reaction takes place at the boundary between the constant-density nucleus and the ash sheath. The "contracting fuel nucleus" model is applied to low-porosity coal with ash which is capable of forming a stable shell. In the "volume reaction" model, it is assumed that combustion takes place throughout the entire volume of the particle (in which case its dimension remains unchanged). As a result, the volumetric concentration of carbon and the density of the particle are decreasing. This model is valid for coals with large amounts of volatiles: after their release, a highly porous structure is formed. In the general case, the outer radius of the particle R, the radius of the fuel nucleus r (the thick-

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ness of the ash layer is R − r), and the average volumetric carbon concentration in the nucleus ψ must all change in proportion to the degree of complete combustion. We use a kinetic equation for the density distribution of particles to describe the dynamics of change in the characteristics of a polydisperse system of combusting coal particles. The kinetic equation, which is written in terms of r, R, and the carbon content in the nucleus $\eta = \psi/\psi_m$, is:

$$\frac{\partial P}{\partial t} + \frac{\partial v_k P}{\partial x_k} + \frac{\partial \dot{r} P}{\partial r} + \frac{\partial \dot{R} P}{\partial R} + \frac{\partial \dot{\eta} P}{\partial \eta} = 0. \tag{1}$$

The function P(R, r, η) determines the probability density that the particles have characteristics r, R, ψ, and Eq. (1) describes the evolution of the polydisperse system of particles in the x_k, r, R, η phase space. This differs from the kinetic equation for particle distribution in terms of R, which is usually used in the theory of polydisperse systems (see, for example [12-15]). In the case considered here of high-ash content fuel combustion, the function P(R) is inadequate for the description of the evolution of the system, and the additional variables r and η are introduced.

The quantities $\dot{r}$, $\dot{R}$, $\dot{\eta}$ in (1) characterize the rate of change of the radius of the fuel nucleus, the particle radius, and the carbon content in the nucleus, as a result of combustion and possibly other processes as well: abrasion, fragmentation, and agglomeration. To simplify analysis, we limit our study of the combustion of carbon to the reaction $C + O_2 = CO_2$. In this case, the decrease in the carbon mass of a coal particle is described by

$$\frac{dm_C}{dt} = -4\pi r^2 \frac{M_C}{M_{O_2}} \rho \sigma k_\Sigma, \tag{2}$$

where k_Σ determines the effective rate of combustion, relative to the surface of the combusting nucleus and the kinetics considered for the heterogeneous reaction. It also determines the diffusion resistance to transport of oxygen from the surrounding medium to the particle surface, and from the outer surface through the ash sheath to the surface of the nucleus:

$$k_\Sigma = \left[\frac{1}{\alpha} + \frac{2r^2}{RD\,\mathrm{Sh}} + \frac{(R-r)r}{RD_a} \right]. \tag{3}$$

Taking the internal reaction into account, the quantity α (the coefficient of the reaction gas-exchange) characterizes the combustion rate in the absence of diffusion retardation. It is determined by

$$\alpha = k(\psi_r + \Delta), \tag{4}$$

where $k = k_0 \exp(-E/R_g T)$, in accordance with an Arrhenius law. According to (4), the quantity α is interpreted as the sum of the rates of surface $k\psi_r$ and internal $k\Delta$ combustion. In this case, the carbon concentration at the surface of the nucleus ψ_r takes into account the decrease in reaction surface due to the presence of ash, and according to [16], the quantity Δ is equal to

$$\Delta = \left(\frac{A}{B} \right)^{1/2} [\mathrm{cth}\,(AB)^{1/2} - (AB)^{-1/2}], \quad A = r\sigma, \quad B = \frac{kr}{D_k}. \tag{5}$$

It follows from (4), (5) that two limiting combustion regimes can exist: the surface (frontal) regime, when the combustion is localized in a thin layer, and a volume regime, when the combustion takes place uniformly throughout the particle.

The regime of surface combustion is realized when $(AB)^{1/2} \gg 1$. Then $\Delta = (A/B)^{1/2}$ and consequently, $\alpha = k\psi_r + (k\sigma D_k)^{1/2}$. The rate of change of the radius of the nucleus, according to (2), (3), is determined by

$$\dot{r} = -\frac{M_C \rho C}{M_{O_2} \rho_C \psi} \left(\frac{1}{k\psi_r + (k\sigma D_k)^{1/2}} + \frac{2r^2}{RD\,\mathrm{Sh}} + \frac{(R-r)r}{RD_a} \right)^{-1}.$$

In the surface combustion regime, the density of the fuel nucleus and its carbon content are unchanging, that is, η = const. Therefore, the last term in (1) is not present. The regime of surface combustion corresponds to the complete combustion of the particle in accordance with the "contracting fuel nucleus" model. Two particular limiting cases of this model are the "segregated ash" model (r = R), and the "conserved ash sheath" model (R = const). In these particular cases, the penultimate term in (1) can be neglected; in the general case, this term describes the change in particle dimension caused by abrasion or any other process.

The regime of volume combustion, when the density of the carbon decreases uniformly throughout the particle volume, is realized when the condition $(AB)^{1/2} \ll 1$, $\Delta = A/3 \gg \psi_r$ is satisfied. In this case, $\alpha = kr\sigma/3$ and $r = R$. If the particle dimension is preserved during combustion (R = const), then (1) simplifies, since the derivatives with respect to r and R will drop out of the equation. According to (2), (3), the rate of change of carbon content is determined by

$$\dot{\eta} = -\frac{M_C \rho C}{M_{O_2} \rho_C} \frac{k\sigma}{1 + 2k\sigma R^2/3D\,\mathrm{Sh}}.$$

The regime of volume reaction is usually realized at low temperatures, when the diffusion resistance to transport of oxygen to the particle surface does not play a significant role, that is, when the internal kinetic combustion law $k_\Sigma = \alpha = kr\sigma/3$ is valid.

Results of simulating the combustion of a fuel in circulating systems were presented in [9, 10], based on the solution to the kinetic equation for the probability density distribution of particles by size. The results pertain to the case of the surface regime of combustion, within the framework of the "outer ash" or "segregated ash" model. We examine the simulation of the complete combustion of a fuel on the basis of the solution to the kinetic equation within the framework of the "volume reaction" model, for an internal kinetic combusion region.

2. To calculate the complete combustion of high-ash particles in the volume-reaction regime, it is necessary to give the relation between the inner surface σ and the carbon content η. The relation $\sigma = \sigma_m \eta$ has been chosen as the simplest dependence [17]. Using this relation, the equation describing the evolution of the combusting polydisperse system of particles in the internal kinetic region takes on the form

$$\frac{\partial P}{\partial t} + \frac{\partial v_k P}{\partial x_k} - \beta \frac{\partial \eta P}{\partial \eta} = 0. \tag{6}$$

The velocity v_k in (6) depends on R and η, which determine the mass of the particle. However, the effect of η on v_k is quite weak, compared to that of R for high-ash content fuel. Therefore, we assume that v_k depends only on R. In assuming that all particles, independent of size or carbon content, have the same temperature, the combustion intensity β is made independent of both R and η. Further, we assume that the grain-size distribution and concentration of carbon of fresh (primordial) fuel placed in the combustion chamber are not correlated:

$$P_1(R, \eta) = P_{R1}(R) P_{\eta 1}(\eta).$$

Taking these assumptions into account, we represent the solution to (6) in the form $P(R, \eta) = R_R(R)P_\eta(\eta)$, which is equivalent to assuming that the probability density distributions by size and carbon content of the fuel particles are independent. The functions P, P_R, and P_η are normalized in the following way:

$$\int_0^\infty \int_0^1 P dR d\eta = n, \quad \int_0^\infty \int_0^1 \frac{4}{3} \pi R^3 P dR d\eta = \varphi,$$

$$P_R = \int_0^1 P d\eta, \quad P_\eta = \frac{1}{\varphi} \int_0^\infty \frac{4}{3} \pi R^3 P dR, \quad \int_0^1 P_\eta d\eta = 1.$$

Taking into account the assumed form for $P(R, \eta)$, we obtain from (6) the following equation for the distribution of fuel particles according to size:

$$\frac{\partial P_R}{\partial t} + \frac{\partial v_k P_R}{\partial x_k} = 0 \tag{7}$$

and carbon content:

$$\frac{\partial \varphi P_\eta}{\partial t} + \frac{\partial \varphi V_k P_\eta}{\partial x_k} - \beta\varphi \frac{\partial \eta P_\eta}{\partial \eta} = 0. \tag{8}$$

The equation describing the change in oxygen concentration C as a result of convective transport and combustion, has the form

$$\frac{\partial C\rho}{\partial t} + \frac{\partial C\rho U_k}{\partial x_k} = -C\rho k\sigma_m \varphi \langle \eta \rangle. \tag{9}$$

We analyze the steady process of complete combustion of the fuel within the limits of the two simplest models widely used in the literature, which depict the motion of the particles in the combustion chamber. These are the models of ideal mixing and ideal displacement. In both cases, the motion of the gas is assumed to be approximated by the model of ideal displacement. In the ideal mixing model, the characteristics of the particle are averaged over the entire volume of the combustion chamber, and thus are independent of the coordinates. (The particle characteristics consist of distribution by size and carbon content, volumetric concentration, velocity, and temperature.) In the ideal displacement model, the change in particle characteristics is considered in a one-dimensional approximation, that is, in one direction only.

In the ideal mixing model, Eq. (7) for the distribution of particles in the combustion chamber by size $\overline{P}_R(R)$ takes the form

$$V_1 P_{R1}(R) + V_2 P_{R2}(R) - \overline{V}(R)\,\overline{P}_R(R) = 0. \tag{10}$$

The fractional composition of particles, trapped in the cyclones and returned to the combustion chamber (i.e., recycled fuel) is related to the grain-size distribution of the particles leaving the combustion chamber and entering the cyclones by the functional relation $V_2P_{R2}(R) = F[\overline{V}(R)\overline{P}_R(R)]$. We assume that this functional can be represented in the form $F[f(R)] = \Phi(R)f(R)$, where $\Phi(R)$ is a function describing the change in the distribution density of the particles by size as a result of separation in the cyclone. Then the solution of (10) has the form

$$\overline{P}_R(R) = \frac{V_1 P_{R1}(R)}{[1 - \Phi(R)]\,\overline{V}(R)}. \tag{11}$$

The change in oxygen mass with height in the combustion chamber, according to (9), is described by

$$\frac{d\rho CU}{dx} = -C\rho k\sigma_m \overline{\varphi}\langle\overline{\eta}\rangle. \tag{12}$$

For an isothermal combustion chamber, the solution of (12) has the form

$$C\rho = C_0\rho_0 \exp\left(-\frac{k\sigma_m\overline{\varphi}\langle\overline{\eta}\rangle}{U_0}x\right),$$

whence

$$\overline{C\rho} = \frac{1}{h}\int_0^h C\rho dx = \frac{C_0\rho_0 U_0}{k\sigma_m\overline{\varphi}\langle\overline{\eta}\rangle h}\left[1 - \exp\left(-\frac{k\sigma_m\overline{\varphi}\langle\overline{\eta}\rangle h}{U_0}\right)\right]. \tag{13}$$

In the ideal mixing model, the equation for the distribution of carbon content (8) takes on the form

$$\beta\overline{\varphi}h\frac{d\eta\overline{P}_\eta}{d\eta} + \overline{\varphi}_1 V_1 P_{\eta 1} + \overline{\varphi}_2 V_2 P_{\eta 2} - \overline{\varphi}\,\overline{V}P_\eta = 0. \tag{14}$$

If combustion does not take place in the cyclone, then there is no change in carbon content as a result of particle motion in the cyclone, and consequently, the distribution of carbon content in the recycled fuel and in the combustion chamber are the same: $P_{\eta 2} = \overline{P}_\eta$. In this case, (14) takes the form

$$\frac{d\eta\overline{P}_\eta}{d\eta} - \gamma\overline{P}_\eta + \gamma P_{\eta 1} = 0. \tag{15}$$

Here,

$$\gamma = \frac{C_0\rho_0/\overline{C\rho}}{\Omega(1+K)}, \quad K = \frac{\varphi_2 V_2}{\varphi_1 V_1}, \quad \Omega = \frac{\beta h}{\overline{V}}.$$

The parameter K is equal to the ratio of the volumetric consumption of recycled and primordial fuel. It characterizes the number of times that the fuel cycles in the combustion chamber-cyclone system. The parameter Ω determines the ratio of the average stay time of the particle in the combustion chamber per cycle of motion in the circulating system h/V to the characteristic time of its complete combustion β^{-1}.

Equation (15) links the distribution of carbon content in the combustion chamber and in the primordial fuel. Its solution, which satisfies the boundary condition $\overline{P}_\eta(1) = 0$ is

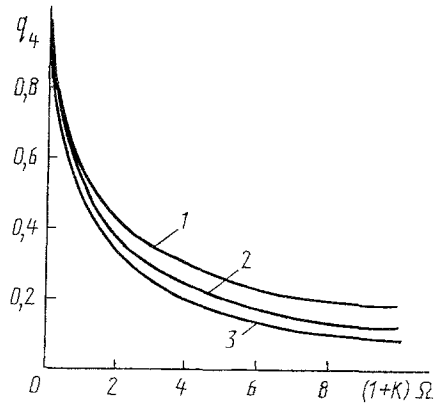

Fig. 1

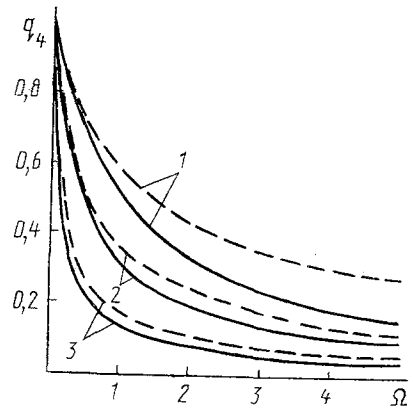

Fig. 2

Fig. 1. Calculation of mechanical underfiring, using the ideal mixing model: 1) $\alpha = 1$; 2) $\alpha = 2$; 3) $\alpha = \infty$.

Fig. 2. Calculation of mechanical underfiring, using the models of ideal displacement and ideal mixing: 1) $K = 0$; 2) $K = 2$; 3) $K = 10$.

$$\overline{P}_\eta = \frac{\gamma}{\eta^{1-\gamma}} \int_\eta^1 \frac{P_{\eta 1}(\xi)}{\xi^\gamma} d\xi. \tag{16}$$

From (16), we determine the average carbon content in the fuel which is located in the combustion chamber:

$$\langle \overline{\eta} \rangle = \frac{\gamma}{1+\gamma} \langle \eta \rangle_1. \tag{17}$$

From (17) it follows that the average carbon content in the combustion chamber does not depend on the distribution of carbon content in the primordial fuel particles, but is determined solely by its average value. The mechanical underfiring of the fuel is determined by the amount of carbon loss with no particles trapped by the cyclone, and is related to the consumption of primordial fuel carbon in the combustion chamber, that is,

$$q_4 = \frac{\langle \overline{\eta} \rangle}{\langle \eta \rangle_1} = \frac{\gamma}{1+\gamma}. \tag{18}$$

By using (13), we obtain from (18) the following relation for determining mechanical underfiring:

$$q_4 = \left\{1 + \frac{\alpha}{q_4}\left[1 - \exp\left(-\frac{(1+K)\Omega}{\alpha} q_4\right)\right]\right\}^{-1}. \tag{19}$$

Expression (19) determines the dependence of q_4 on the parameters Ω, K, and the coefficient of excess air $\alpha = M_C \rho_0 C_0 U_0 / M_{O_2} \rho_C \varphi_1 \langle \eta \rangle_1 V_1$. Figure 1 shows q_4 as a function of the quantity $(1 + K)\Omega$, which characterizes the ratio of the average stay time of the particle in the combustion chamber to the characteristic time of complete combustion. Naturally, with growth in the coefficient of excess air, the value of the mechanical underfiring decreases: for $\alpha \to \infty$, it follows from (19) that $q_4 = [1 + (1 + K)\Omega]^{-1}$.

In the ideal displacement model, Eq. (7) for the distribution function of particles by size in the combustion chamber takes the form

$$\frac{\partial v_x P_R}{\partial x} = 0. \tag{20}$$

The solution to (20) is:

$$P_R(R, x) = \frac{V_1 P_{R1}(R)}{[1 - \Phi(R)]\, v_x(R, x)},$$

that is, essentially it coincides with (11), which was obtained in the ideal mixing model approximation, except that in the ideal displacement model, change in the distribution function P_R by height in the combustion chamber can be taken into account. This change comes about as a consequence of the change in the rate of motion of the particles v_x.

In this approximation, Eq. (8) for the distribution function for the carbon content takes the form

$$\frac{\partial \varphi V_x P_\eta}{\partial x} - \beta\varphi \frac{\partial \eta P_\eta}{\partial \eta} = 0. \tag{21}$$

Taking the relation $\varphi V_x = \varphi_0 V_{x0}$ into account, the solution to (21) is

$$P_\eta(\eta, x) = e^X P_{\eta 0}(e^X \eta), \quad X = \int_0^x \frac{\beta}{V_x} dx, \tag{22}$$

where $P_{\eta 0}(\eta)$ is the distribution function for carbon content in the particles for x = 0, which is determined as a result of mixing primordial and recycled fuel at the entrance to the combustion chamber:

$$P_{\eta 0}(\eta) = \frac{\varphi_1 V_1 P_{\eta 1}(\eta) + \varphi_2 V_2 P_{\eta 2}(\eta)}{\varphi_1 V_1 + \varphi_2 V_2}.$$

If there is no combustion in the cyclone, then the distribution functions for carbon content in the recycled fuel and at the exit from the combustion chamber are the same, and consequently:

$$P_\eta(\eta) = \frac{P_{\eta 1}(\eta) + K e^{X_h} P_{\eta 0}(e^{X_h}\eta)}{1 + K}, \quad X_h = \int_0^h \frac{\beta dx}{V_x}. \tag{23}$$

According to (22), (23), the change in the average carbon content in the fuel particles with height in the combustion chamber is described by

$$\langle \eta \rangle = \exp(-X) \langle \eta \rangle_0 = \frac{\exp(-X) \langle \eta \rangle_1}{1 + K - K \exp(-X_h)}. \tag{24}$$

Thus according to (22)-(24), in order to calculate the distribution function and the average value for the carbon content in the fuel, the dependence X(x) must be known. Towards this end, we must determine the change with chamber height of the mass concentration of oxygen, which enters into the intensity of combustion β. In the case when the change in temperature with height is insignificant, and the flow can be considered as approximately isothermal, the relation $U = U_0$ is valid. Then the mass concentration of the oxygen is related to the average carbon content by

$$\frac{C\rho}{C_0\rho_0} = 1 - \frac{1 + K}{\alpha}\left(\frac{\langle \eta \rangle_0 - \langle \eta \rangle}{\langle \eta \rangle_1}\right), \tag{25}$$

which expresses the condition of the balance of C and O_2 mass fluxes as a result of combustion.

From (22), (23), and (25) we obtain the following:

$$\frac{dX}{dX_0} = 1 - \Lambda[1 - \exp(-X)],$$

$$X_0 = \int_0^x \frac{\beta_0}{V_x} dx, \quad \Lambda = \frac{(1 + K)}{\alpha[1 + K - K\exp(-X_h)]}. \tag{26}$$

The solution of (26), satisfying boundary condition X = 0 at $X_0 = 0$, is

$$\frac{1}{1 - \Lambda} \ln[\Lambda + (1 - \Lambda)\exp X] = X_0. \tag{27}$$

The quantity $X_{0h} = \int_0^h \frac{\beta_0 dx}{V_x}$ can be identified with the parameter Ω, which characterizes the process of complete combustion of the particles in the ideal mixing model approximation. Then, according to (27), the quantity X_h is determined by

$$\frac{1}{1 - \Lambda} \ln[\Lambda + (1 - \Lambda)\exp X_h] = \Omega. \tag{28}$$

Mechanical underfiring of the fuel due to loss in the cyclone, with average carbon content in the particles equal to the value at the exit from the combustion chamber, is found from

$$q_4 = \frac{\langle \eta \rangle_h}{\langle \eta \rangle_1} = \frac{\exp(-X_h)}{1 + K - K\exp(-X_h)}. \tag{29}$$

The solid lines in Fig. 2 show q_4 as a function of Ω, constructed according to (28), (29) for different circulation numbers K. It is evident, that with growth in Ω and K, the mechanical underfiring is decreased, since the stay time of the fuel in the combustion chamber is increased. The effect of the coefficient of excess air α on q_4 is naturally the same as that in Fig. 1 for the ideal mixing model: for $\alpha \to \infty$ ($\Lambda \to 0$), it follows from (28) and (29) that $q_4 = \exp(-\Omega)[1 + K - K\exp(-\Omega)]^{-1}$. The dashed lines in Fig. 2 show the values of q_4 computed from (19). The values of q_4, obtained according to the model of ideal displacement and ideal mixing, give lower and upper bounds, respectively, on the mechanical underfiring which is valid under realistic conditions for the motion of particles in the combustion chamber.

NOTATION

t, time; v_k, particle velocity; ψ_m, maximum volumetric concentration of carbon in the primordial fuel; ρ, gas density; C, mass concentration of oxygen in the gas; M_C, M_{O_2}, molecular masses of carbon and oxygen; D, D_a, D_k, coefficients of diffusion of the oxygen in surrounding medium, the ash sheath, and in the nucleus; Sh, Sherwood number; E, activation energy; T, temperature; σ, inner surface of the carbon per unit volume; σ_m, maximum inner surface of the carbon in a primordial fuel; $m_C = 4\pi R^3 \rho_C \psi/3$, mass of the carbon in a particle; ρ_C, density of the carbon; $\beta = M_C C \rho k \sigma_m / M_{O_2} \rho_C$, combustion intensity; $\beta_0 = M_C C_0 \rho_0 k \sigma_m / M_{O_2} \rho_C$; n, number of particles per unit volume; φ, volumetric concentration of particles in space; U, velocity of the gas; h, height of the combustion chamber; $V_k = \frac{1}{\varphi}\int_0^\infty \frac{4}{3}\pi R^3 v_k P_R dR$, average particle velocity; $\langle\eta\rangle = \int_0^1 \eta P_\eta d\eta$, average carbon content in the particles; $\bar{V}(R)$, rate of particle transport from the combustion chamber; $\varphi = \int_0^\infty \frac{4}{3}\pi R^3 \bar{P}_R dR$, volumetric concentration of the particles in the combustion chamber; $\langle\bar{\eta}\rangle = \int_0^1 \eta \bar{P}_\eta d\eta$, average carbon content in the fuel located in the combustion chamber; $\bar{v} = \frac{1}{\varphi}\int_0^\infty \frac{4}{3}\pi R^3 \bar{V} \bar{P}_R dR$, average rate of particle transport from the combustion chamber. Indices: 0, parameters at the entrance to the combustion chamber (x = 0); 1 denotes particles of primordial fuel; 2, those of recycled fuel.

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