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Parametric domain of the stationary filtration combustion wave in the charge with a low carbon content

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The dependences of the temperature and the rate of filtration combustion (FC) of carbon on the main parameters controlling the process were experimentally and theoretically studied. Among these are the fraction of the combustible in the charge, the flow rate of the oxidant, the reactivity of the carbon material, and the level of heat loss *via* the reactor walls. The transition from the conditions of stationary propagation of the combustion wave to decay occurs critically, upon a minor change in the controlling parameters. The parametric domain of the stationary wave was determined. A simplified unidimensional one-temperature mathematical model was proposed for the description of stationary regimes of FC of solid fuels. The model qualitatively characterizes the dependence of the combustion regime on the main controlling parameters and makes it possible to reveal the critical conditions for the existence of stationary combustion regimes.

Key words: combustion, macrokinetics, carbon, oxidation kinetics, filtration, charge, heat loss.

Filtration combustion (FC) of solid fuel implies the propagation of waves of the exothermic conversion of a combustible in a porous medium during the filtration of the oxidant gas.[1] The macrokinetic characteristics of the FC (temperature and velocity of wave propagation) depends on numerous factors, including the chemical nature and fraction of the combustible in the charge, the flow rate of the oxidant, and heat exchange rate. Under certain conditions, the FC occurs in a stationary regime. In this case, the front of the combustion wave moves with a constant velocity and the heat released is concentrated in a rather narrow zone, thus providing the conditions for the so-called superadiabatic heating.[1]

The study of the FC characteristics is important for revealing regularities of wave processes and specific features of the occurrence of diverse chemical transformations. This investigation also helps to determine the regions of optimum conditions providing advantages of the FC in technological processes. The theoretical models were developed that make it possible (for simple kinetic schemes) to determine the dependences of the macrokinetic characteristics in the combustion wave on the flow rate and composition of the oxidant.[1—3]

The calculation of the macrokinetic characteristics of in-situ combustion of a coal layer in the mountain mass showed that with heat loss, there exists the minimum concentration of the oxidant in the gas below which the stationary FC wave propagation becomes impossible (lower concentration limit).[4] As a result of numerical calculations, the region of existence of the FC wave determined by the level of heat loss, the oxidant flow rate, and the fraction of the oxidant in the gas was obtained.

For mixtures of a carbon material and an inert diluent, the experimental dependences of the characteristics of filtration combustion wave on the flow rate of the gaseous reactant and the carbon content in the charge at the fraction of the combustible lower than 7 wt.% were measured.[5,6] The lower limit of carbon concentration for FC was determined and it was shown that at a fixed level of heat loss the obtained values depend on the reactivity of the carbon material and the oxidant flow rate.

The present work describes results of experimental and theoretically study of the influence of the air flow rate and heat loss on the values of the lower concentration limit imposed on the existence of the filtration combustion stationary wave for three carbon materials with different structures and reactivities.

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Experimental

The filtration combustion of carbon samples was carried out in a 250 mm long cylindrical reactor with an inner diameter of 25 mm (Fig. 1). The conditions of external heat exchange providing different levels of heat loss were varied using a removable aluminum screen reflecting the radiation of the hot reactor; the effective heat exchange coefficient (α) of the reactor with the screen was 6 W m^{-2} K^{-1}, and that without the screen was α = 12 W m^{-2} K^{-1} (the procedure for the determination of α is described below).

The charge consisted of particles of a carbon material and an inert filler. Technical sapphire was used as an inert material. The particle size of the inert filler was 2—3 mm, and the weight was 20—60 mg. The particles were irregular polyhedra with irregular faces and projections; at a low carbon concentration in the charge this resulted in the formation of a framework immobile upon burning out of the combustible.

Birch-tree active carbon BAU-A (GOST 6214-74; density (ρ) 0.4 g cm^{-3}, specific surface (S_{sp}) 400 m^2 g^{-1}), birch charcoal (BC) (GOST 7657-84; ρ = 0.38 g cm^{-3}, S_{sp} = 1.1 m^2 g^{-1}), and the carbon—carbon fiber composite material (CC) (ρ = 1.42 g cm^{-3}, S_{sp} = 0.2 m^2 g^{-1}) (see Ref. 7) were used as the combustibles. The particle size of the combustibles was 1—2 mm, and the weight was 1—3 mg (birch coals) or 5—15 mg (composite). The properties of the carbon samples, including the kinetic parameters of oxidation in the isothermal regime, are presented in Table 1. The data of Table 1 show that listed above modifications of carbon have different reactivities: birch coal is most reactive in oxidation and carbon composite has the lowest reactivity.

Dry (relative humidity less than 1%) air served as an oxidant. The air flow rate V (volumetric air discharge per unit cross-section of the reactor) was measured by the pressure drop on the capillary calibrated with a water rotamer. The variation range for V was $(2—15) \cdot 10^{-2}$ m s^{-1}, and the absolute inaccuracy of measurements did not exceed $1.1 \cdot 10^{-3}$ m s^{-1}.

Chromel—alumel thermocouples with a diameter of 0.2 mm were used for temperature measurements in the FC wave. The thermojunctions were placed on the axial line of the reactor (see Fig. 1).

The linear velocity of FC wave propagation was determined as $U = L_{i,j}/(t_i - t_j)$, where $L_{i,j}$ is the distance between the ith and jth thermocouples in the reactor; and t_i and t_j are the times needed for the FC wave front to pass through the corresponding thermocouples (determined as inflections points of the dependences $T_i(t)$ in the region of charge heating ahead of the front, Fig. 2, *a*).

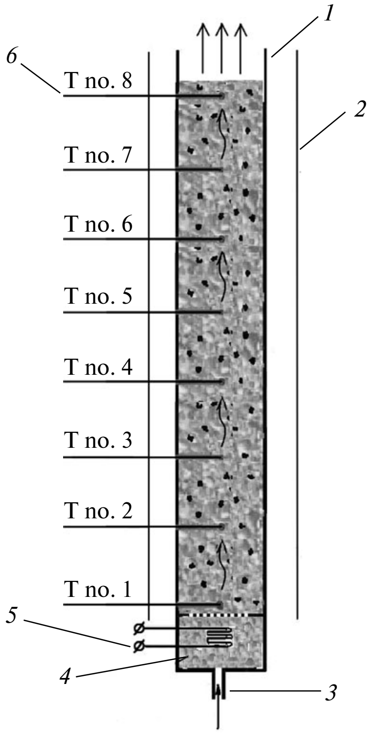

Fig. 1. Reactor of filtration combustion: *1*, quartz tube filled with the charge; *2*, aluminum screen; *3*, air supply tube; *4*, load of the inert material; *5*, electric coil; and *6*, thermocouples (T) nos 1—8.

Since the conditions for combustion depend on the reactivity of a combustible, either low- or high-temperature initiation of the combustion wave was performed. For the low-temperature initiation, the cartridge at the inlet of the reactor was heated with an electric coil to ~800 K, and then the charge was loaded and the oxidant was fed. The maximum temperature of the convective heat wave at the inlet of the reactor measured by thermocouple no. 1 reached 773 K in this case.

To obtain a higher initiation temperature, a layer of the initiating charge with a high content (8%) of birch charcoal and a thickness of 3—5 cm was loaded on the reactor bottom. Then the charge under study was loaded. The initiating layer was ignited with a flow rate of 0.2—0.3 m s^{-1}. The necessary gas flow

Table 1. Pre-exponential factors and the activation energy of the monomolecular and formally autocatalytic reactions of carbon oxidation[6]

Sample	$\log(k_1/\text{s}^{-1})$ [E_{a_1}/kJ mol^{-1}]	$\log(k_2/\text{s}^{-1})$, [E_{a_2}/kJ mol^{-1}]	Temperature of oxidation/K
Birch charcoal (GOST 7657-84)	2.92 [77]	—	523—623
Birch-tree active carbon (GOST 6214-74)	3.15 [98]	5.13 [100]	573—673
Carbon composite	1.72 [113]	—	823—1073

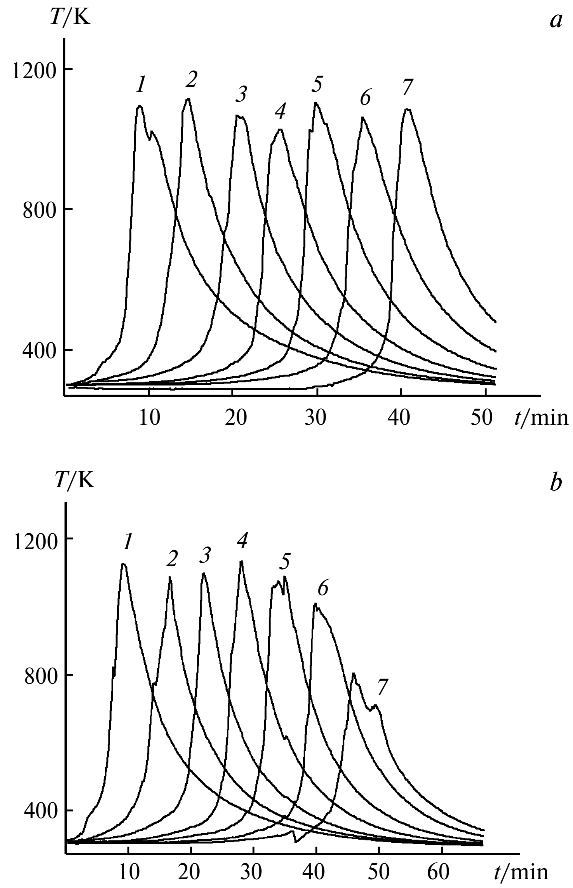

Fig. 2. Temperature profiles of the FC wave in the charge containing 5 wt.% active carbon at the distance z = 30 (*1*), 60 (*2*), 90 (*3*), 120 (*4*), 150 (*5*), 180 (*6*), and 210 mm (*7*) from the inlet of the reactor (without the screen). The flow rate of air is V = 0.09 (*a*) and 0.07 m s^{-1} (*b*).

rate was established after the combustion of the initiating mixture. For this method of initiating, the maximum temperature of the wave at the transition from the initiation zone to the studied mixture reached 1473 K.

Figures 2, *a* and *b* present the experimental temperature profiles of the FC wave in the charge containing 5 wt.% active carbon at the air flow rate V = 0.09 (see Fig. 2, *a*) and 0.07 m s^{-1} (see Fig. 2, *b*).

Figure 2, *a* shows that the temperature profiles on the consecutive thermocouples that are identical in shape with the shift in time; in this case, the FC regime is assigned stationary. Figure 2, *b* illustrates the propagation of wave that decays on passing over the length of this reactor. In all cases of the established stationary combustion wave, the macrokinetic parameters of the FC were independent of the initiation regime (low- or high-temperature).

For sampling gaseous combustion products, glass gas burettes 80—100 cm^3 in volume were used, which were pre-evacuated to a residual pressure of ~1 Pa. Sampling was carried out directly from the charge layer through a capillary, the end of which was placed at a distance of 5—9 cm from the surface to prevent ingress of air from the atmosphere. The combustion products were analyzed on an MX-1302 mass spectrometer.

Theoretical model

The simplified unidimensional one-temperature mathematical model taking into account lateral heat losses was used to describe the stationary regime of filtration combustion of carbon.

The model was constructed with the following assumptions.

1. The combustion wave propagates in a sufficiently long tubular reactor, where the temperature and concentration distribution in the charge layer is unidimensional and depends on the coordinate along the reactor axis only (unidimensionality).

2. The oxidation of carbon to CO_2 proceeds *via* a single reaction route. The experimental results presented below confirm that this assumption is justified at low concentrations of the combustible in the initial mixture; in this case, the oxidation rate is proportional to the concentrations of carbon and oxygen.

3. In each cross-section of the reactor, the temperatures of the gaseous and solid phases coincide (one-temperature character).

4. Heat and mass transfer by diffusion in the gas is negligible compared to the convective heat and mass transfer.

5. The thermal conductivity in the material layer is described by a linear law with the constant coefficient, and the heat loss is described by the effective coefficient of heat exchange, which is temperature-independent.

We additionally assumed that the pressure drop on the reactor is low: the pressure in each point of the reactor is considered constant. The fixed mass flow rate of the gas coming to the reactor was specified.

With the above assumptions, the established stationary regime of carbon combustion in the reactor can be described (in the reference frame of the combustion front) with the equations given below.

Energy balance equation

$$\lambda\frac{d^2T}{dz^2}+\frac{dT}{dz}(S-F)-\frac{2\alpha}{r}(T-T_0)+QW=0, \qquad (1)$$

where $S = U\sum_j \rho_{sj}C_{sj}$ is the heat capacity of the solid phase flow; and $F = V\sum_j \rho_{gj}C_{gj}$ is the heat capacity of the gas flow (summation over all components in respective phase).

Carbon mass balance

$$-U\frac{d\rho_c}{dz}=-W. \qquad (2)$$

Oxidant (oxygen) mass balance

$$V\frac{d\rho_x}{dz}=-W. \qquad (3)$$

Expression for the flow rate of the inert component of the gas (nitrogen)

$$G_n{}^0 = V\rho_n. \qquad (4)$$

Expression for the chemical reaction rate

$$W = k_0\rho_x\rho_c\exp[-E/(RT)]. \qquad (5)$$

The reactor can be considered infinite, because the height of the charge column exceeds the extension of the heating and cooling zones; therefore, the equations set is closed by the following boundary conditions (Fig. 3):

at $z = -\infty$ (at the inlet of the reactor): $T = T_0$, $\rho_x = \rho_x^0$, $\rho_c = 0$;

at $z = +\infty$ (at the outlet of the reactor): $T = T_0$, $\rho_x = \rho_x^*$, $\rho_c = \rho_c^0$.

The following notation is used in Eqs (1)—(5) and hereinafter: V/m s^{-1} is the gas flow rate; U/m s^{-1} is the solid phase velocity (the value coincides with that of combustion front propagation along the charge layer in the laboratory system of coordinates); T/K is temperature; z/m is the coordinate, the point of origin coincides with the combustion front (burning occurs at a peak temperature); ρ/kg m^{-3} (mol m^{-3}) is the density (concentration) of the substance; C/J kg^{-1} K^{-1} (J mol^{-1} K^{-1}) is the specific heat capacity; Q/J mol^{-1} is the heat of the chemical reaction; r/m is the radius of the reactor; W/mol m^{-3} s^{-1} is the chemical reaction rate; G/mol m^{-2} s^{-1} is the consumption rate of the gaseous component; α/W m^{-2} K^{-1} is the effective coefficient of heat exchange; and λ/W m^{-1} K^{-1} is the effective coefficient of thermal conductivity of the charge. Indices: s is the solid phase; g is the gas; x is oxygen; c is carbon; n is nitrogen of air; b is the value in the combustion zone; 0 is the initial value; and asterisk (*) shows the unknown value to be determined.

At a small content of the combustible in the initial mixture, the structure of the combustion wave is reaction-leading one,[1] in which two zones of inert heat exchange can be distinguished (see Fig. 3). The first zone (I, cooling zone) is located in front of the combustion front upstream the gas flow. Solid reaction products are cooled in zone I. The second zone (II, heating zone) is situated behind the combustion front, where gaseous reaction products are cooled. Relatively narrow combustion zone, in which the main heat release occurs due to the chemical reactions, lies between the heat exchange zones.

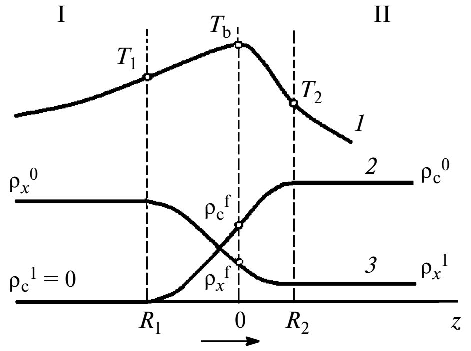

Fig. 3. Schematic profiles of temperature (*1*) and concentration (*2, 3*) of the active components in the case of the reaction-leading structure of the FC wave: *2*, ρ_c and *3*, ρ_x (ρ_c^f and ρ_x^f are the values of density of oxygen and carbon in the front of the combustion wave).

As can be seen from Fig. 3, in the heat exchange zones, where the chemical reaction rate is low, the concentrations of reactive components remain unchanged and, hence, the mass balance equations can be ignored. In the heat exchange zones, Eqs (1)—(3) take the form

$$\lambda\frac{d^2T}{dz^2} + (S - F)\frac{dT}{dz} - \frac{2\alpha}{r}(T - T_0) = 0;$$

$$\rho_c = 0,\ \rho_x = \rho_x^0,\ -\infty < z < R_1; \qquad (6)$$

$$\rho_c = \rho_c^0,\ \rho_x = \rho_x^*,\ R_2 < z < +\infty,$$

where R_1 and R_2 are the coordinates of the beginning and end of the zone of carbon oxidation, respectively.

The solutions of the heat conduction equation (6) describe the temperature profiles in cooling (I) and heating (II) zones

$$T_{\mathrm{I}} = T_0 + (T_b - T_0)\exp(m_2 z),\ -\infty < z < 0;$$

$$T_{\mathrm{II}} = T_0 + (T_b - T_0)\exp(m_1 z),\ 0 < z < +\infty,$$

where $m_{1,2} = -(S - F)\dfrac{1 \pm \sqrt{1 + 8\alpha\lambda/[r(S - F)^2]}}{2\lambda}$ are two roots of the characteristic equation.

In the combustion zone the temperature reaches maximum and the chemical reaction rate increases sharply; therefore, the equations describing transformations of the reactants should be included into the system. Since we believe that the combustion zone is rather narrow, the terms responsible for the convection and heat loss in the energy balance equation can be ignored. In this case, for $R_1 < z < R_2$ we have

$$\begin{cases} \lambda\dfrac{d^2T}{dz^2} + QW = 0 \\ -U\dfrac{d\rho_c}{dz} = -W \\ V\dfrac{d\rho_x}{dz} = -W \\ W = k_0\exp[-E/(RT)]\rho_x\rho_c \end{cases} \qquad (7)$$

with the boundary conditions

$$\begin{cases} \rho_c(R_1) = 0 \\ \rho_c(R_2) = \rho_c^0 \\ \rho_x(R_1) = \rho_x^0 \\ \rho_x(R_2) = \rho_x^*. \end{cases}$$

The boundary conditions reflect the complete consumption of carbon in the FC wave, because for the reaction-leading structure of the FC wave the extended cooling zone is observed, where residual carbon is exposed to a high temperature in a flow of freshly fed air. Note that in all experiments, where the stable propagation of the FC wave was observed, no traces of incompletely burnt carbon were detected in the charge after the wave has passed. The residual oxygen concentration in the gaseous products, on the contrary, can be non-zero due to the quenching of the products upon the fast cooling of the gas in the relatively narrow zone of charge heating.

By excluding the value of W from the system of energy and oxygen mass balance equations (7) and integrating the obtained expression over the narrow reaction zone, we have

$$\lambda \frac{\mathrm{d}T}{\mathrm{d}z}\bigg|_{z=R_2} - \lambda \frac{\mathrm{d}T}{\mathrm{d}z}\bigg|_{z=R_1} = QG_x\big|_{z=R_2} - QG_x\big|_{z=R_1}.$$

The first and second terms in the left-hand part of this equation are obtained by the differentiation with respect to the coordinate of the expressions for the temperature in the heating zone (T_{II}) and in the cooling zone (T_{I}) going to the limit at $z \to 0$. Taking into account the boundary conditions for the combustion zone and assuming continuity of the temperature in the combustion zone (*i.e.*, $T|_{z=R_1\to 0} = T|_{z=R_2\to 0}$), we have

$$T_{\mathrm{b}} = T_0 + \frac{Q(G_x^0 - G_x^*)}{\lambda(m_2 - m_1)}. \qquad (8)$$

Since the concentrations of the components involved in the reaction are related by one stoichiometric equation, the concentration of one component can be expressed through the concentration of another component. For this purpose, we exclude the value of W from the system of carbon and oxygen mass balance equation (7), subtracting the second equation from the third equation and integrating with allowance for the boundary conditions. We see that

$$\rho_x^* = \rho_x^0 - \frac{U\rho_{\mathrm{c}}^0}{V}. \qquad (9)$$

Similarly, excluding W from the equations of energy and carbon mass balance (7) gives

$$\lambda \frac{\mathrm{d}T}{\mathrm{d}z} + QU\rho_{\mathrm{c}} = C_1. \qquad (10)$$

Constant C_1 is found from the boundary conditions at $z = R_1$ ($\rho_{\mathrm{c}} = 0$)

$$\lambda \frac{\mathrm{d}T_1}{\mathrm{d}z}\bigg|_{z=R_1\to 0} = C_1.$$

Taking into account the equation for temperature in the cooling zone, we obtain the expression for constant C_1

$$C_1 = (T_{\mathrm{b}} - T_0)\lambda m_2.$$

Dividing expression (10) by the carbon mass balance equation, we obtain equation that readily integrates

$$\int_{T_0}^{T_{\mathrm{b}}} \exp[-E/(RT)]\mathrm{d}T = \frac{U}{\lambda k_0}\int_{\rho_{\mathrm{c}}^0}^{\rho_{\mathrm{c}}^*} \frac{C_1 - QU\rho_{\mathrm{c}}}{\rho_x\rho_{\mathrm{c}}}\mathrm{d}\rho_{\mathrm{c}}.$$

Let us write the boundary conditions for the combustion zone: $z = (0, R_2)$, $T = (T_{\mathrm{b}}, T^*)$, $\rho_{\mathrm{c}} = (\rho_{\mathrm{c}}^*, \rho_{\mathrm{c}}^0)$, where T^* is the temperature at which a noticeable heat release starts, and ρ_{c}^* is the carbon concentration at $z = 0$ ($\rho_{\mathrm{c}}^* \neq 0$ due to the heat flow from the combustion zone to the cooling zone). The integration limits in the first integral can be extended to T_0, because the integrand rapidly approaches zero at temperatures lower than T^*. To find the integral in the left-hand part of the equation, let us expand the exponent to the Taylor series in the vicinity of the maximum value of the temperature (similarly to the Frank-Kamenetskii transform[8]). Let us calculate the integral in the right-hand part and substitute ρ_x from Eq. (9). As a result, we have

$$\frac{RT_{\mathrm{b}}^2}{E}\exp[-E/(RT_{\mathrm{b}})] = \frac{U}{\lambda k_0}\left(VQ\ln\left[\frac{G_x^0 - U\rho_{\mathrm{c}}^*}{G_x^*}\right] - \right.$$
$$\left. - \frac{\lambda m_2(T_{\mathrm{b}} - T_0)}{\rho_x^0}\ln\left[\frac{G_x^0 - U\rho_{\mathrm{c}}^*}{G_x^0}\cdot\frac{\rho_{\mathrm{c}}^0}{\rho_x^*}\right]\right). \qquad (11)$$

Equation (11) provides an interrelation between the combustion temperature, wave propagation velocity, and kinetic parameters of the carbon oxidation reaction. In this equation, the value of ρ_{c}^* remains an uncertain quantity, *viz.*, the carbon density at $z = 0$, which can be found from Eq. (10) using the boundary conditions at $z = 0$: $\mathrm{d}T/\mathrm{d}z = 0$, $\rho_{\mathrm{c}} = \rho_{\mathrm{c}}^*$.

$$\rho_x^* = \frac{(T_{\mathrm{b}} - T_0)\lambda m_2}{UQ}.$$

The solution in the final form looks as follows:

$$\left\{\begin{aligned}
& T_{\mathrm{b}} = T_0 + \frac{Q(G_x^0 - G_x^*)}{\lambda(m_2 - m_1)} \\
& \rho_x^* = \rho_x^0 - \frac{U\rho_{\mathrm{c}}^0}{V} \\
& \frac{RT_{\mathrm{b}}^2}{E}\exp[-E/(RT_{\mathrm{b}})] = \frac{U}{\lambda k_0}\left(VQ\ln\left[\frac{G_x^0 - U\rho_{\mathrm{c}}^*}{\mathrm{G}_{\mathrm{x}}^*}\right] - \right. \\
& \qquad \left. - \frac{\lambda m_2(T_{\mathrm{b}} - T_0)}{\rho_x^0}\ln\left[\frac{G_x^0 - U\rho_{\mathrm{c}}^*}{G_x^0\rho_x^*}\cdot\frac{\rho_{\mathrm{c}}^0}{\rho_x^*}\right]\right)
\end{aligned}\right. \qquad (12)$$

$$
\begin{cases}
\rho_x^* = \dfrac{(T_b - T_0)\lambda m_2}{UQ} \\[2ex]
m_1 = -(S - F)\dfrac{1 + \sqrt{1 + 8\alpha\lambda/\left[r(S - F)^2\right]}}{2\lambda} \\[2ex]
m_2 = -(S - F)\dfrac{1 - \sqrt{1 + 8\alpha\lambda/\left[r(S - F)^2\right]}}{2\lambda}
\end{cases}
$$

The equations set (12) gives the dependence of the combustion temperature (T_b), wave propagation velocity (U), concentrations of carbon and oxygen at $z = 0$ ($\rho_c{}^*$ and $\rho_x{}^*$, respectively), and exponents m_1 and m_2 on the control parameters of the process (the gas flow rate and the initial concentrations of the reactants) and the kinetic and thermophysical characteristics. The characteristics of the FC wave are not explicitly expressed in the analytical form from Eqs (12); hence, further we find the dependences by the numerical solution of the equation set.

Results and Discussion

The calculations were performed for the values of parameters corresponding to the characteristics of the reactor and charge used in experiment. The values of k_0 and E were chosen on the basis of independent experiments on the kinetics of oxidation of the studied samples[9]; $T_0 = 300$ K is the temperature of the environment; $C_g = 29.27$ J mol^{-1} K^{-1} and $\rho_g = 34.5$ mol m^{-3} are the specific heat capacity and the density of the gas, respectively; and $C_s = 77.62$ J mol^{-1} K^{-1} is the specific heat capacity of the solid phase.

The solution of Eq. (6) provides a possibility to find the effective coefficients of thermal conductivity and heat exchange for the system under study. The values of λ and α were determined as fit parameters providing description for the entire array of the experimental data. For this purpose, the dependences $T(t)$ obtained in experiment (see Fig. 2, *a*) were brought to the form

$$T(z) = T[U(t_b - t)],$$

where t_b is the time moment corresponding to the maximum value of temperature. The time dependence of the temperature in the heating and cooling zones are satisfactorily described by exponential functions. For the highest accuracy of calculations, experiments with the maximum values of $(S - F)$ were taken from the data array. Coefficients λ and α were determined as fit parameters providing the best approximation of the experimental temperature profiles to the exponential functions.

The parametric domain of the stationary FC wave was determined as follows. The solution of equations set (12) was construed by incrementally decreasing the carbon concentration in the charge and the air flow rate. When the solution of system (12) ceases to exist upon a decrease of one of the varied parameters by the value of increment (0.1 wt.% and 0.005 m s^{-1}, respectively), this is interpreted as the decay of the FC wave under these conditions.

Figure 4 presents, for the mixtures containing active carbon BAU-A, the experimentally determined and calculated dependences for the lower concentration limit of the FC wave existence at varied level of the heat loss on the oxidant flow rate. With the increasing oxidant flow rate, the region of existence of the stationary FC wave extends toward the lower concentration of carbon in the initial mixture. As the oxidant flow rate decreases, the fraction of carbon, at which the stationary propagation of the combustion wave is possible, somewhat increases, and the critical carbon concentration increases sharply after some value of oxidant flow rate is achieved. This means that the mixtures should be enriched in carbon for stable FC. With an increase in the level of lateral heat loss, the region of the stationary combustion wave shifts toward higher values of oxidant flow rate and higher carbon concentrations. As can be seen from Fig. 4, the calculated dependences of the lower concentration limit on the air flow rate and heat loss are similar to the experimental dependences. The best coincidence of the boundary of the stationary FC wave existence is observed at low air flow rates and relatively high concentration of carbon when the oxidant is completely consumed in the combustion zone.

The region of the stationary FC wave is also affected by the reactivity of a combustible. The change in the boundaries of the region with a change in the kinetic parameters of carbon oxidation was observed both in the calculation and experimentally (Fig. 5). The lowest oxidant flow rates and concentrations of carbon at which the sta-

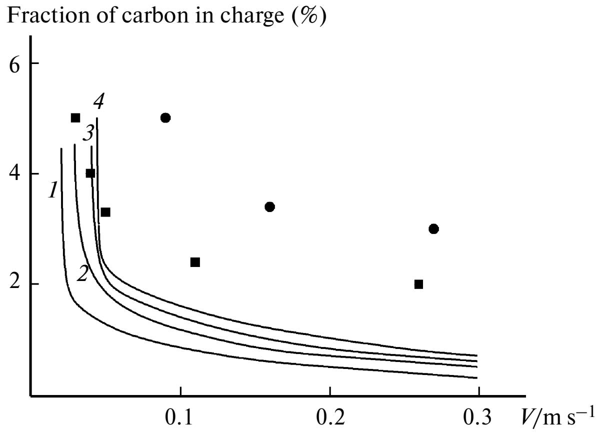

Fig. 4. Boundaries of the parametric domain of stationary FC waves in the charge with active carbon. Curves are the calculation for α = 5 (*1*), 10 (*2*), 15 (*3*), and 20 W m^{-2} K^{-1} (*4*); and points are the boundary values of the controlling parameters at which the stationary FC is still observed: α = 6 (squares) and 12 W m^{-2} K^{-1} (circles).

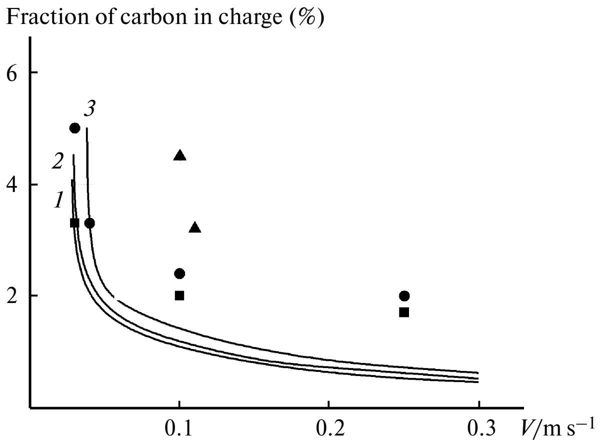

Fig. 5. Boundaries of the parametric domain of stationary FC waves in the charge with birch-tree carbon BC (*1*, squares), active carbon BAU-A (*2*, circles), and the carbon composite (*3*, triangles): curves are calculation, and points are the boundary values of the controlling parameters at which the stationary FC is still observed; $\alpha = 12$ W m^{-2} K^{-1}.

tionary FC wave exists are recorded for the charge with the most reactive birch charcoal, whereas the highest values (narrowing of the parametric region of the stationary wave) are recorded for the least reactive carbon composite.

For the combustible concentration corresponding to the reaction-leading structure of the wave, the combustion temperature decreases with a decrease in the carbon fraction when carbon is diluted with the inert material in the charge (with a decrease in the carbon fraction). This temperature decrease results in an incomplete consumption of oxygen in the combustion wave, which, in turn, causes a decrease in the mass rate of carbon consumption.

The calculated and experimental dependences of the volume oxygen fraction in the combustion products of the charge containing 3.4 wt.% active carbon on the air flow rate are shown in Fig. 6. In the experiment, the air flow rate (*V*) equal to 0.03 m s^{-1} corresponds to the critical one; the decay of the combustion wave was observed at lower values. The data presented in Fig. 6 show that near the low concentration limit the fraction of oxygen in the products increases from 3 to 8 vol.% with a decrease in *V* from 0.04 to 0.03 m s^{-1}. At $V > 0.04$ m s^{-1}, a reverse trend is visible. Some increase in the temperature of the process is observed with an increase in the air flow rate; however, the fraction of unreacted oxygen in the gaseous products increases due to a shorter residence time of oxygen in the combustion zone.

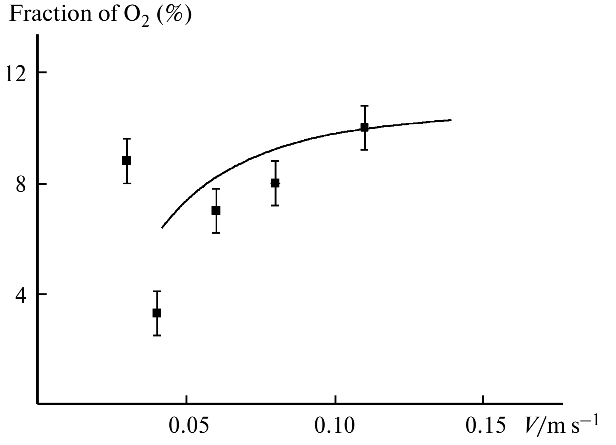

Fig. 6. Volume fraction of oxygen in the combustion products *vs* air flow rate for the charge containing 3.4 wt.% active carbon: curve is calculation, and points are experiment; $\alpha = 12$ W m^{-2} K^{-1}.

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Thus, for the fixed level of heat loss, the lower concentration limit of the existence of the filtration combustion wave of the solid fuel depends on the flow rate of the gaseous oxidant and reactivity of the combustible. With an increase in the flow rate of the gaseous oxidant and for a higher reactivity of the combustible, the parametric domain of the existence of the stationary combustion wave extends toward a lower content of combustible in the initial mixture.

The filtration combustion wave can remain stable even at a very small content of the combustible in the charge.

The quantitative differences in the calculated and experimental values of the lower concentration limit are inevitable in view of the roughness of the kinetic and thermophysical models. At the same time, the simulation results are qualitatively consistent with experiment, indicating that the model proposed reveals the mechanism of FC wave decay and describes the character of the dependence of the parameters, at which stationary combustion is possible, on the conditions of the process.

It should be noted in conclusion that the stability of propagation of the stationary combustion wave was previously considered[10] for the systems, whose the combustion of which obeys the Zeldovich mechanism, that dictates that the velocity of wave propagation is determined by the rates of the chemical reaction and heat transfer. In the FC regimes of heterogeneous systems, the velocity of combustion wave propagation is determined by the rate of oxidant supply. The approach of Ref. 10 could be applied for the systems studied in the present work, although it should be based on other combustion mechanisms that would take into account the difference in rate-controlling steps.

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