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TRANSITION FROM THE REGIME OF LOW RATES OF FILTRATION COMBUSTION OF GASES TO THE REGIME OF HIGH RATES WITH A PRESSURE INCREASE

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Regularities of the transition from the regime of low rates (RLR) of filtration combustion (FC) of gases to the regime of high rates (RHR) with a pressure increase are investigated. It is shown that allowance for gas-phase transfer is important for description of FC, at least when the size of the skeleton pores $d > 1.5-2.0$ mm and the calorific power of the fuel exceeds the limit of propagation of the flame. With an increase of 1–2 atm in the working pressure as compared to atmospheric pressure the critical pore size decreases by a factor of 2.0–2.5. A theoretical model that makes it possible to evaluate the velocities and temperatures of FC stationary waves under conditions of the transition from RLR to RHR and to establish realization limits for these regimes is proposed. It is shown that a more adequate description of the transient regime and the regime of high rates is achieved when the turbulent character of the combustion is allowed for.

Filtration combustion (FC) of gases attracts great interest in connection with use of it for burning of lean fuels, for catalyst reactivation, and in other thermochemical processes [1, 2]. Possible regimes of propagation of flames in porous media are considered and classified in [3-6]. Thus, the regime of low rates (RLR) is characterized by a combustion rate relative to the skeleton of the solid phase of the order of 0.1 mm/sec, the basic regularities of wave propagation being governed by intense interphase heat transfer and the heat conduction of the skeleton. The regime of high rates (RHR) is characterized by a rate of the order of 1 m/sec and is controlled by gas-phase transfer and, to a lesser extent, interphase transfer.

Historically, much attention has been paid to investigating the combustion of lean fuels at superadiabatic temperatures [2, 7]. Under these conditions, the position of the gas-phase combustion front is determined by the coordinate of activation of the exothermal reaction in heating of gas from the skeleton. Therefore the effect of gas-phase transfer, including turbulent transfer, on the localization of combustion was disregarded in the corresponding FC models [8-11]. The satisfactory accuracy and simplicity of this approach led to its wide use in modeling the RLR of FC [1, 5, 7-11]. Quantitative and qualitative determination of the applicability limits of this approach remains an important problem. Much effort has been directed toward more realistic consideration of the combustion kinetics [12] and allowance for interphase transfer [1, 13, 14]. Stationary FC was modeled in [13], a two-dimensional two-temperature model with a discrete solid phase and simpler volume-averaged one-dimensional models being used. In spite of considerable difficulty in modeling, the results of [13] reduce to finding of a satisfactory agreement of the results of the models in question for macroscopic (averaged) temperatures and combustion rates (a typical disagreement between the two-dimensional and one-dimensional two-temperature models with averaged parameters of heat transfer is 10%), while point temperatures and combustion rates in a pore can vary within 20%. The transient FC regime from RLR to RHR was not considered in the work. Quantitative and qualitative features of this transition are of considerable practical interest since it is characterized by

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acceleration of countermotion of the wave, the occurrence of velocity and pressure pulsations, and a jump or even damping of the flame.

A general view of the interrelationship between RLR and RHR is given in [4, 5]. Using the equations for the combustion-wave velocity it is shown that, for finite heat-transfer coefficients, RLR becomes RHR as the pore size d increases; a region of values of d exists in which both RLR and RHR (depending on the initial state of the system) can be realized. The zone of an "uncertain" regime was not interpreted physically in detail and an experimental check was not performed.

In [15], a one-dimensional model that simulates the discrete structure of a filtration channel in a porous body was used for investigating FC. As a result of nonstationary calculations it was shown that the character of the FC changes as the size of the solid-phase particles and the filtration rate increase. Fluctuations of the combustion rate occur at a particle size that exceeds $D_{cr1} \sim 3-4$ mm, and the RHR is realized when the size $D_{cr2} \sim 8$ mm is exceeded.

Dynamic and frequency characteristics of the FC of the RLR in tubes filled with ceramic pellets as functions of the filtration rate and the composition of the gas were investigated experimentally in [16] along with capillary combustion.

Thus, in spite of a certain model understanding of the processes in an FC wave under conditions of an RLR-to-RHR transition [4, 5, 15], this transition in a field of various parameters in real burners with a porous charge has not been studied experimentally. Furthermore, there is no analytical model of the transient regime of FC that is quite simple and at the same time allows for the complex character of the heat- and mass-transfer processes.

Another important problem in the theory of FC is the effect of turbulence on its characteristics. This problem was touched upon in a number of works ([1, 3, 14] and others). Here, on the one hand, the important role of the turbulence of the flow in heat-transfer and combustion processes was stressed [5], and, on the other, its unclear character and mechanism were pointed to, and, in this connection, the possibility itself of using the term "turbulence" at Re $\sim 30-300$ was disputed. In this connection, we note that, as applied to the FC conditions in question, by "turbulence" we understand complex motion of a gas that includes vortex, shear, and pulsation elements.

In this work, an attempt is made to answer to a certain degree the above questions. For this purpose, a model of the transient regime is proposed where the ratio of the intensity of gas-phase transfer (including turbulent transfer) in a flame to the intensity of interphase heat transfer is used as the basic parameter. The model makes it possible to parameterize the entire transition region of FC from the RLR, in which gas-phase transfer is insignificant (solid-phase ignition, SI), to the RHR proper and to describe qualitatively the features of this transition observed in experiment. Based on the model proposed, we can determine the role of turbulence more accurately by comparing the results of theory obtained, on the one hand, with allowance for the turbulent character of the combustion and, on the other, without allowance for this character. Using it we can also evaluate the applicability limit for simplified models that do not allow for gas-phase transfer, as we can evaluate the region where these assumptions are not valid. A simple method for determining the velocity and temperature of an FC wave for the transient regime is proposed. By the "transient regime" we usually understand a regime of FC in which its macroscopic parameters change abruptly. Here we use the term "transient" broadly, meaning an FC regime in which gas-phase transfer, including turbulent transfer, has a substantial effect on the macroscopic characteristics of the process.

In a series of experiments, we measured the velocity of FC-wave propagation in a real burner for different pressures in the wave front and flow rates of the fuel. Regimes in which strong velocity and pressure pulsations and a jump and damping of the flame occur are noted. A comparison with the described theoretical model is made.

Theory of the Transient Regime of FC. Strong interphase heat transfer in FC leads to "tying" of the region of chemical reaction in the gas to a certain high-temperature region of the skeleton, which corresponds to the regime of low rates with solid phase ignition, the RLR of SI (Fig. 1). Progress of the flame is possible only together with movement of the heat wave in the skeleton. When heat transfer with the skeleton is attenuated, the region of intense chemical reaction can move or fluctuate in the pore space, and as the interphase heat transfer is attenuated further,

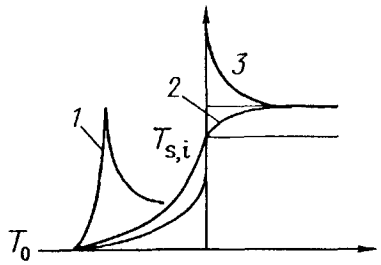

Fig. 1. Temperature profiles in FC: 1) gas temperature in a jump, 2) solid-skeleton temperature, 3) gas temperature in the regime of low rates. $T_{s,i}$ is the ignition temperature.

it can move into another pore or start moving toward the flow. The latter situation corresponds to a so-called jump of the flame, or the RHR. For it to be realized, it is necessary that:

1) the rate of gas combustion be higher than the filtration rate, $S > u_g$;

2) the heat losses of the flame not exceed the limiting value at which it is damped.

We consider the first condition to be fulfilled in practically important cases of FC (Re $\sim 10-1000$) for mixtures with a heat content sufficient for propagation of the flame, since here the rate of turbulent combustion can substantially exceed the rate of normal combustion of the gas [5, 6, 17-19]. The Zel'dovich hypothesis [17] of the turbulent-combustion rate being equal to the sum of the maximum pulsation velocity and the normal laminar combustion rate, $S = u'_g + S_n$, yields the same, since $u'_g \approx u_g$ is fulfilled in filtration. To assess fulfillment of the second condition, by analogy with [5] we compare the time of thermal relaxation of the flame τ_t and the characteristic burning time τ_b. Cooling of the gas in a channel of diameter d, specific surface area S_{sp}, and wall temperature T_0 is described as

$$2\frac{d^2\theta}{d\xi^2} - \mathrm{Pe}\frac{d\theta}{d\xi} - \frac{1}{2}S_{sp}d\,\mathrm{Nu}\,\theta = 0 \tag{1}$$

with the boundary conditions $\theta = 1$ when $\xi = 0$ and $\theta = 0$ when $\xi = \infty$. Here $\theta = (T - T_0)/(T_{ad} - T_0)$, $\xi = x/r$, Nu $= hd/\lambda$, Pe $= u_g d/\kappa$, $\kappa = \lambda/(c\rho)$, $d = 2r$, the remaining notation is standard and is listed in Notation. For a cylindrical channel, $S_{sp}r = 2$, and the solution of (1) has the form

$$\theta = \exp(-a\xi), \tag{2}$$

where

$$a = \frac{\mathrm{Pe}}{4}\left[\left(1 + 16\frac{\mathrm{Nu}}{\mathrm{Pe}^2}\right)^{1/2} - 1\right] \approx 2\frac{\mathrm{Nu}}{\mathrm{Pe}}.$$

The temperature interval of activation of the reaction is defined as βT_{ad}, where $\beta = RT_{ad}/E$ [17]. This makes it possible to evaluate the characteristic distance and the time of thermal relaxation of the gas:

$$\xi_t = \frac{RT_{ad}^2}{E(T_{ad} - T_0)} \Big/ a, \quad \tau_t = \frac{\xi_t d/2}{u_g} = \frac{1}{4}\frac{RT_{ad}^2}{E(T_{ad} - T_0)}\frac{c\rho d}{h}. \tag{3}$$

The characteristic burning time can be expressed in terms of the rate of normal laminar combustion S_n: $\tau_b = \kappa/S_n^2$ [17]; however, this evaluation will be substantially understated, since it fails to allow for the turbulent character of the flame. At the moment, there is no universally adopted model of gas-phase transfer in FC. Therefore, in our opinion, it is appropriate to resort to semi-empirical models of free turbulent combustion, making provisoes. According to the theory, the functional dependence of the turbulent-flame velocity depends on the regime realized. We distinguish the regime of a "wrinkled" flame, the regime of distributed reaction zones, and a

regime intermediate between them [19-21]. The first is realized at smaller Reynolds numbers, the combustion rate being controlled mainly by the deformation of the flame front (hence the name) and to a lesser extent by the intensification of heat and mass transfer due to shears and vortices. Physically, this regime is closest to FC for characteristic Reynolds numbers Re ~30–500. According to [19-21], the combustion rate in the regime of a "wrinkled" flame can be expressed in terms of the velocity of the normal laminar flame S_n, the intensity of turbulent pulsations u', and the integral turbulence scale L:

$$S/S_n \sim \mathrm{Re}_{L,u'}^{1/4}, \quad \mathrm{Re}_{L,u'} \equiv u'L/\nu .$$

The integral turbulence scale and the intensity of turbulent pulsations in FC are prescribed in a natural manner as d and u_g, and therefore

$$\tau_b = \kappa/S_n^2/\mathrm{Re}^{1/2}. \tag{4}$$

The condition of a flame jump defined as $\tau_t > \tau_b$, in view of (3) and (4), will be written as

$$\frac{1}{4}\frac{RT_{ad}^2}{E(T_{ad}-T_0)}\frac{c\rho d}{h} > \frac{\kappa}{S_n^2\,\mathrm{Re}^{1/2}}. \tag{5}$$

We introduce $\mathrm{Pe} = S_n d/\kappa$ and will use this definition throughout the article. We rewrite (5), using the Nusselt number:

$$\beta\,\mathrm{Pe}^2\,\mathrm{Re}^{1/2} > 4\,\mathrm{Nu}\,(T_{ad}-T_0)/T_{ad}.$$

By assuming [22] $\mathrm{Nu} = 0.395\mathrm{Re}^{0.64}$ and $\mathrm{Pr}^{0.33} \approx 0.35\mathrm{Re}^{2/3}$ (for $30 < \mathrm{Re} < 5\cdot 10^5$) we obtain

$$\Phi \equiv \frac{\beta \mathrm{Pe}^2}{\mathrm{Re}^{1/6}} > 1.4\,\frac{T_{ad}-T_0}{T_{ad}}. \tag{6}$$

According to the physical model of thermal relaxation, T_{ad} in formulas (5) and (6) is the maximum gas temperature, while T_0 is the skeleton temperature that corresponds to the coordinate of the gas "flash." Here, T_0 is easily evaluated as the ignition temperature $T_{s,i}$ [10] or the ambient temperature – depending on the physical situation. The maximum gas temperature is a very complex function of the parameters of the system. So as not to burden the model with cumbersome implicit formulas, we evaluate the maximum temperature of the gas in (6) as the adiabatic combustion temperature of this mixture T_{ad}. A certain confidence in the validity of this evaluation is provided by the fact that it is exact in the two limiting cases $\alpha \to 0$ and $\alpha \to \infty$ (for a stationary wave) and at some intermediate point of the transient regime of FC $\alpha = \mathrm{const}$. According to the aforesaid, the numbers Pe and Re that enter in (6) are calculated at the temperature T_{ad}. An alternative evaluation of τ_b based on the velocity of the normal laminar flame leads to the following condition instead of (6):

$$\Phi' \equiv \frac{\beta \mathrm{Pe}_S^2}{\mathrm{Re}^{2/3}} > 1.4\,\frac{T_{ad}-T_0}{T_{ad}}. \tag{7}$$

It follows from (6) that when the skeleton temperature is high ($T_0 \sim T_{ad}$) the flame jumps at any Pe. For a cold skeleton, $(T_{ad} - T_0) \approx T_{ad}$ is fulfilled, and (6) yields

$$\Phi > 1.4. \tag{8}$$

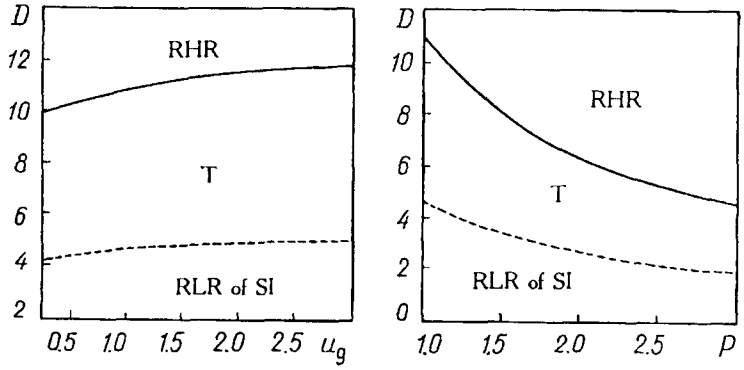

Fig. 2. Diameter of the pellets of the porous charge (mm) that corresponds to different FC regimes: RLR of SI, transient regime (T), and RHR. A stoichiometric methane-air mixture. Calculation by (9) at fixed pressure (P = 1 atm) and rate (u_g = 1 m/sec).

If condition (8) holds for the average pore size but the pore channels have significant variances in diameter and geometry, a flame that separates from a high-temperature front can be divided by isolated pore channels. Consequently, immediately ahead of the region of parameters that correspond to the RHR there must exist a region of irregular behavior of the front where small-scale jumps of the flame, low-frequency or single pressure pulses, and other phenomena are possible.

Since the parameter Φ characterizes the ability of the gas-phase flame to move under filtration conditions no matter what the solid phase, there exists a limiting value of Φ for which this movement (position fluctuation) is impossible, which corresponds to the RLR of SI. Let us determine this value. The temperature of the surroundings of the skeleton T_0 in Eqs. (1)-(7) corresponds to the ignition temperature $T_{s,i}$ in FC models (Fig. 1). According to the model of [10] that deals with the RLR of SI, the relation $T_{s,i} > 0.8T_{ad}$ is fulfilled in a nearly stationary case of FC. Taking this into account, we assume that $(T_{ad} - T_0)T_{ad} < 0.2$ in formula (6) and obtain a condition under which gas-phase transfer has a substantial effect on localization of combustion:

$$\Phi > 0.28 . \tag{9}$$

Thus, when the relation $\Phi < 0.28$ that is inverse to (9) is fulfilled, the RLR of SI occurs. In the parameter region determined by (8) the RHR is realized; irregular behavior of the flame is possible just before it. In the intermediate region of the parameters, we need to allow for gas-phase transfer, and pulsations of the position of the combustion front, the pressure, and the velocity can appear. It should be noted that the fluctuations of the position of the combustion front in a real porous body are usually random and nonresonant in character (unlike combustion in a capillary [16], where regular fluctuations are observed). The fact that the combustion is continuous in time is fundamental. (Our understanding of the behavior of a gas-phase flame in the transient regime of FC is somewhat different from [15], where oscillations are invariably related to extinction–ignition of the mixture.) A different situation arises when the chemical-reaction front jumps into a neighboring (or another distant) pore where it decays. In this case, new ignition of the mixture occurs that produces a substantially more powerful push of the pressure and the temperature. Although the frequency of quenching-ignition pulses is expressed in an obvious manner in terms of the filtration rate and the width of the front in the solid phase, the amplitude of the pulses and the frequency of resonant oscillations are related to the resonance properties of the system as a whole. We find a condition for occurrence of strong pulsations from the following physical considerations. We consider the characteristic length of an exponential temperature decrease in the heating zone to be equal to the distance between skeleton pores [1, 7]. Then when the gas-phase flame jumps into a neighboring pore (in the direction opposite the flow) the ambient temperature is evaluated as $T_0 \approx T_{ad}/e$. Substituting this quantity into (6), we obtain a condition for occurrence of strong pulsations:

$$\Phi = 0.9 . \tag{10}$$

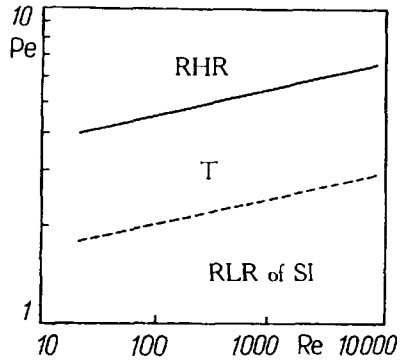

Fig. 3. Diagram of the regions of filtration-combustion regimes: RLR of SI, transient regime (T), and RHR in coordinates of Re–Pe for a stoichiometric methane–air mixture.

Inequality (8) enables us to evaluate the critical size of the skeleton pores required for the RHR to begin:

$$d > \left(\frac{1.4}{\beta} \frac{u_g^{1/6}}{S_n^2} \frac{\kappa^2}{\nu^{1/6}} \right)^{6/11} . \tag{11}$$

Figure 2 presents curves that delimit regions of the RLR, the transient regime (T), and the RHR of FC calculated for a stoichiometric methane-air mixture according to (8) and (9). The pore diameter and the charge-pellet diameter were assumed to be related by $d = \frac{2}{3} \frac{m}{1-m} D$ [1, 12]. We adopted the energy of methane-combustion activation in units of temperature as $E/R = 15{,}098$ K [9]. The adiabatic temperature of the flame, the normal combustion rate, and other data are taken from [14]. It is of interest to note that the boundaries of the regimes (as corrected for nomenclature) calculated by our model agree to a good degree of accuracy with the calculation of [15]. A diagram of Re–Pe for the methane-air mixture that is based on (8) and (9) is given in Fig. 3.

Relations (6)-(9) that parameterize the transition region of FC have a qualitative evaluational character. However the relative change in Φ corresponds more exactly to the change in the combustion regime. Consequently, rewriting (6)-(9) accurate to a constant A, we obtain more exact expressions for the transient regime provided that the constant is found experimentally:

$$\Phi > A \quad \text{is the RHR}, \tag{12}$$

$$\Phi = 0.65A \quad \text{is pulsations of quenching–ignition of the mixture}, \tag{13}$$

$$\Phi > 0.2A \quad \text{is the RLR of SI}. \tag{14}$$

As has been indicated above, a number of models of the RLR of FC (in particular, all one-temperature models) fail to allow for gas-phase transfer and combustion-turbulence effects and, therefore, are adequate only for the RLR of SI. They can be reconstructed to a certain extent to allow for the transient RLR of FC. For this purpose we note that a displacement of the zone of gas-phase combustion relative to the skeleton is equivalent (from the viewpoint of the simplified models of [8-11]) to a decrease in the ignition temperature $T_{s,i}$ (see Fig. 1). Approximation of the ignition temperature with account for (6) and (14) yields

$$T_{s,i} = \tilde{T}_{s,i} (1.2 - \Phi/A), \tag{15}$$

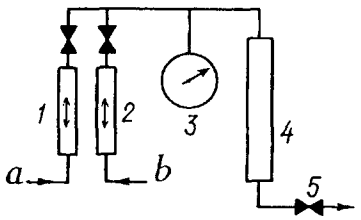

Fig. 4. Scheme of the experimental setup: 1, 2) rotameters [a) air, b) propane–butane]; 3) manometer; 4) burner; 5) stopcock.

where $0.2 < \Phi/A < 0.65$; $\tilde{T}_{s,i}$ is the ignition temperature calculated without allowance for gas-phase transfer or turbulence. We note that (15) is inapplicable for nonstationary regimes of the wave and when pulsations and a jump of the flame occur ($\Phi/A > 0.65$).

Experiment. Experiments on the propagation of FC waves were conducted on the setup shown schematically in Fig. 4. The reactor was a 60-cm-long steel tube with an inside diameter of 65 mm and a wall thickness of 2.5 mm. Premixed propane–butane and air were the combustible gas. The flow rate and composition of the mixture were set and maintained by rotameters. The pressure at the inlet to the reactor was varied in the range of 1.0–3.5 atm. A charge of pellets of aluminum oxide Al_2O_3 5 mm in diameter was used as the porous skeleton. The adopted parameters of the charge were: a porosity of 1.4; a heat capacity of Al_2O_3 of 1250 J/(kg·K); a density with allowance for the porosity of 1.56 kg/dm^3; a thermal conductivity of 1.5 W/(m·K) [8]. Ignition was performed by a spark plug placed in the charge. As the charge pellets were heated, an FC wave formed and propagated. The direction of the filtration flow is taken as the positive direction of wave propagation. The wave velocity was measured from the movement of the incandescent zone on the tube surface as the average of several successive measurements performed with a 2–5 min interval. The measurement with the largest deviation from the average was dropped, the characteristic root-mean-square error for a sample being about 30%. The excess pressure at the inlet of the tube was measured by a manometer and was set by the position of the outlet stopcock. The velocity of the filtration flow was calculated based on the total flow rate of the fuel mixture, the cross section of the tube, and the porosity of the charge and was reduced to normal conditions. The values of Φ and Φ' were calculated according to (6) and (7) for each experiment. We assumed $E/R = 15{,}098$ K [23] and $\beta = T_{ad}/15{,}098$ for the butane–propane mixture. The adiabatic temperature of the flame was taken from [18]. The magnitude of the wave velocity in substantially transient regimes was not recorded. Results of the measurements and calculations are presented in Table 1.

Investigation of the processes of FC showed qualitative changes in its character as the pressure increases. A substantial increase to 0.2 mm/sec in the velocity of counterpropagation of the combustion-wave front (experiments 8 and 13) with the simultaneous appearance of pressure and gas-velocity pulsations (experiments 7, 8, 12-16) was noted. The characteristic pulsation frequency was 5–10 Hz, which is much lower than the resonant acoustic frequencies of the system and is close to the frequency of quenching–ignition of the fuel at the length of the skeleton's temperature front. The frequency characteristics were not investigated in detail. If the pulsations led to leaning of the fuel because of misadjustment of the gas-supply system, they ceased. We were able to achieve a similar effect by decreasing the pressure in the system and (or) leaning the composition of the mixture using the control cocks of the setup. In the case of experiments 22 and 23 at a pressure of 3 atm we observed short-duration (consisting of series of 1-5 beats) that were enhanced when the gas mixture was enriched slightly. Short-duration pulsations were noted in experiment 8 (2.5 atm) upon slight enrichment of the gas–air mixture.

In experiments 7, 12, 15, and 16, against a background of strong beats, we observed decay of the combustion wave with characteristic decay times of 2.5 min (experiment 7) and 1 min (experiments 15 and 16). The amplitude and frequency of the beats decreased with temperature in the combustion zone. Some time after decay of the combustion at the site of its initial localization (disappearance of the red glow of the burner tube) a high-temperature zone formed at the upper flange of the experimental burner; the distance from the site of the decay to the upper flange was 15–40 cm in different experiments.

Additional investigations of the character of combustion-wave propagation in a medium with a 2–3 mm charge showed the absence of unstable regimes of combustion in the parameter range of experiments 1-14. If there

TABLE 1. Data on FC of a Propane–Butane–Air Mixture in a Charge of Al_2O_3 Pellets, $D = 5$ mm

No. of experiment	Equivalent ratio	P, atm	u_{g0}, m/sec	u, mm/sec	Φ, (6)	Φ', (7)
1	0.87	1.5	1.42	−0.06	0.283	0.044
2	0.87	1.5	1.79	−0.04	0.273	0.038
3	0.87	1.5	2.02	−0.028	0.268	0.035
4	0.87	2	1.65	−016	0.42	0.06
5	0.87	2	2.1	−0.11	0.40	0.051
6	0.87	2	2.36	−0.1	0.397	0.047
7	0.87	2.5	1.24		0.61[b,c]	0.1
8	0.87	2.5	1.55	−0.2	0.59[b]	0.087
9	0.87	2.5	1.85	−0.15	0.57	0.077
10	0.87	2.5	2.36	−0.127	0.55	0.066
11	0.87	2.5	2.66	−0.05	0.54	0.061
12	0.87	3	2.03		0.73[b,c]	0.095
13	0.87	3	2.58	−0.2	0.70[b]	0.081
14	0.87	3	2.91	−0.06	0.695[b]	0.075
15	0.87	3.25	1.38		0.88[b,c]	0.14
16	0.87	3.5	3.2		0.86[b,c]	0.088
17	0.69	1.5	1.78	0.06	0.258	0.034
18	0.69	2	2.08	0.01	0.382	0.047
19	0.69	2	2.61	0.05	0.37	0.04
20	0.69	2.5	2.35	0.007	0.52	0.059
21	0.69	2.5	2.94	0.0125	0.50	0.051
22	0.69	3	2.56	−0.037	0.67[a]	0.073
23	0.69	3	3.24	−0.0042	0.644[a]	0.062
24	0.62	1.5	2.0	0.04	0.23	0.028
25	0.62	2	2.34	0.054	0.34	0.038
26	0.62	2	2.6	0.1125	0.335	0.036
27	0.62	2.5	2.64	0.047	0.46	0.048
28	0.62	2.5	2.93	0.0104	0.455	0.045
29	0.62	3	2.88	0	0.57	0.06
30	0.62	3	3.23	0.054	0.586	0.055

Note: a is a regime bordering the pulsations; b is pulsations of the pressure and the filtration rate of the gas; c is a jump of the flame and decay and movement of the combustion front.

was an interface between two charges (magnesite sand of $D = 3$ mm and Al_2O_3 pellets of $D = 5$ mm) in the reactor, then when the boundary was reached by the combustion front in the regime of experiments 12-14 we observed sharp extinction of it in the finely granular charge and a jump of 3–4 cm opposite the flow in the Al_2O_3 charge.

Discussion of the Results. From the data of Table 1 it can be seen that the parameter Φ is of the order of unity, which means that the effect of gas-phase transfer and turbulence of combustion can be substantial in this region of the FC parameters. The pressure oscillations and flame jumps observed confirm this. The FC-wave velocity was calculated using the simplified two-temperature model of [10] and was corrected according to (15). Lateral heat losses were allowed for according to [11], although this played no pronounced role. Figure 5 presents results of calculations that correspond to experiments 1-6. As the plots show, correction for the transient regime governs both the qualitative and quantitative regularities of propagation of the flame front. Disregarding gas-phase transfer in the FC model leads to the fact that the wave velocity does not depend on the pressure (for the prescribed mass flow rate) and is substantially overevaluated.

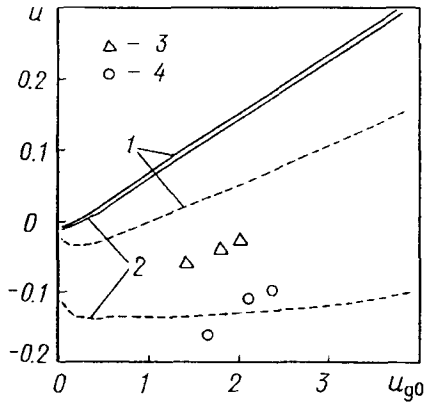

Fig. 5. Velocity of the FC wave u, mm/sec, vs. filtration rate u_{g0}, m/sec, reduced to normal temperature and pressure. The solid lines denote calculation by the model of [7], the dashed lines denote calculation according to (15); 1) $P = 1.5$ atm; 2) 2.0; 3) experiments 1-3; 4) experiments 4-6.

The increase in the parameter Φ as the pressure increases and the flow rate of the gas decreases corresponds to the enhanced role of gas-phase transfer and turbulence in FC. According to the experiments, the critical value of Φ for the beginning of oscillations is $\Phi_{osc} \sim 0.6$.

The parameter Φ' constructed on the normal laminar combustion rate describes the experiments more poorly than Φ. First, its value has a large spread for the physically similar situations of experiments 7, 12, 15, 16 and 22, 23 as compared to the spread in Φ values. Second, in experiments 4, 9, 10, and 11 its value is approximately equal to or larger than that in 22 and 23, although we observed no pulsations. Thus, the experiments confirm the concept of an important role for turbulence in the transient regime of FC adopted in this work. To judge the details of turbulent transfer in FC, we need to accumulate abundant experimental material.

As follows from experiments 12, 15, and 16, the region of parameters $\Phi \geq 0.7$ corresponds to a jump of the flame and the beginning of the regime of high FC rates. According to the physical understanding of the processes, at the boundary of the RHR region we observe irregular jumps of the combustion front, as a result of which the flame front can be divided and (or) quenched. This boundary regime is very interesting and is rich in thermophysical and dynamic phenomena. Thus, after the beginning of spontaneous jumps of the flame the maximum skeleton temperature decreases, which leads to a decrease in the hydrodynamic resistance of the porous body and a decrease in the pressure in the system. As a result the stationary RLR of FC can be restored and a cyclic process that consists of RLR and RHR phases of FC can occur. We note that the dynamic behavior of the flame in the boundary region depends on the design of the reactor, the adjustment of the supply system, etc. Unfortunately, when pulsations occur it becomes impossible to maintain (to measure) stable supply of the system using float rotameters. This gave us no way of judging to the required degree of accuracy the parameters of the beginning of a jump and decay of the flame.

Checking the given theory for other charges and porous bodies and studying nonstationary and quasiperiodic processes of FC that occur at the boundary between the RHR and the RLR can be a continuation of this investigation.

NOTATION

S, velocity of flame propagation; S_n, velocity of the normal laminar flame; u, velocity of the FC front; u_g, average rate of filtration of the gas; u_{g0}, gas-filtration rate reduced to normal temperature and pressure; r and d, radius and diameter of a pore channel; D, diameter of a charge pellet; m, porosity of the skeleton; S_{sp}, specific surface of a volume element of the porous skeleton; T and T_{ad}, gas temperature and adiabatic combustion temperature of the gas mixture; T_0, temperature of the filtration-channel walls or skeleton temperature at the coordinate of the flame; E/R, activation energy of the reaction in degrees; c, specific heat at constant pressure; ρ, bulk density; λ, thermal conductivity; h, heat-transfer coefficient; κ, thermal diffusivity; ν, kinematic viscosity; τ_t

and τ_b, characteristic thermal-relaxation and burning times of the gas under filtration conditions. Subscripts and superscripts: g, gas phase; s, solid phase; i, ignition; b, burning; t, thermal; sp, specific quantity; n, normal laminar (for the flame).

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