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PARALLELS BETWEEN THE REGIMES OF TURBULENT AND FILTRATION COMBUSTION OF GASES IN INERT POROUS MEDIA

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The parallels between the turbulent and the filtration combustion of a gas in an inert medium have been considered. It is suggested that in the case where the thermal interaction between the gas and the porous medium is absent, elementary processes of mixing, chemical reaction, and others, which occur in turbulent and filtration combustion, can be characterized by similar dimensionless parameters setting up a correspondence between the integral scale of turbulence and the size of the pores. The dimensionless parameters have been analyzed and the diagram of the Borghi regimes of filtration combustion has been constructed. A number of typical cases of filtration combustion have been characterized using this diagram. It is shown that the considered cases of filtration combustion concern the range of distorted flames and distributed reaction zones according to the Borghi classification. From this it was assumed that the surface of filtration combustion in the first of the considered regimes is continuous in character. The formulas for estimating the rate of gas-phase combustion under filtration conditions have been recommended.

Introduction. Problems of filtration combustion (FC) of gases have been studied rather intensively in recent years in connection with technological applications of this process to reclamation (oxidization) of noxious gases, burning of superlean fuels, treatment of catalysts in a heat wave, realization of specific chemical processes, etc. Important results in this area have been obtained by Russian and Belarusian scientists [1–3].

Against the background of active studies of thermophysical and chemical aspects of filtration combustion, the problem of the structure of a gas flame in filtration combustion has been left practically untouched. Its importance is attributed to the fact that it is precisely the structure of a gas flame that determines the quantitative and qualitative characteristics of the change from the low-rate regime to a high-rate regime of filtration combustion and of the high-rate regime itself and also the adequacy of models of filtration combustion, which are used in engineering and research practice. In this case, the problem of determining the characteristics of the gas flame is very difficult in both the experimental and theoretical respects. This is explained by the fact that the structure of a porous body and of the filtration field is irregular, the internal pores are practically inaccessible for optical and probe measurements, etc. On the other hand, there are a number of works devoted to the study of the characteristics of the internal velocity field in filtration [4–6]. The data of these and other investigations allow the conclusion that even for filtration rates corresponding to Reynolds numbers of the order of 30 the velocity field is characterized by marked irregular pulsations and the existence of vortices. This raises the question of whether the experience accumulated in the modeling of turbulent combustion (TC) can be used for description of the combustion of the gas under filtration conditions. To do this, one can use the classification of turbulent-combustion regimes [7–9] and find the correspondence

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between the turbulent and the filtration combustion. For each regime of turbulent combustion there are a great number of models describing the dynamic and structural characteristics of the flame, which, after a modification, can be applied to filtration combustion and used to understand the process at the physical level.

The construction of parallels between different physical processes implies that both processes are presented by similar mathematical relations. In this case, the dimensionless parameters used for description of one process can be transformed to describe the other. If the thermal interaction between the solid and the gas phases is disregarded in filtration (adiabatic gas phase), it may be suggested that the processes of heat and mass transfer in the gas phase, which determine the rate of the turbulent and the filtration combustion, are the same. Certain grounds for this supposition are provided by the fact that the simplest models of turbulent and filtration combustion are identical. For example, the known Damköhler model of turbulent combustion [10], which operates with the area of cones formed by a pulsating flow, can reasonably be applied to filtration combustion. Since the present-day applied models of turbulent combustion describe a number of elementary processes, such as mixing at the laminar-flame length, mixing at the total length, etc., and the processes themselves are characterized by dimensionless parameters, one can be quite sure that, having found a similarity between such parameters, one can extend the correspondence between the turbulent and the filtration combustion to more complex models of combustion.

In the present work, an attempt has been made to determine the parallels between the turbulent and the filtration combustion of a gas. From this standpoint, the regimes of filtration combustion realized in certain experiments and production units have been characterized and the conclusions of the character of the gas-phase flame have been drawn. It is shown how the results of the present work can be used for determining the characteristics of the change from the low-rate regime (LRR) of filtration combustion to a high-rate regime (HRR).

Basic Parameters of the Turbulent-Combustion Theory. In studies of the hydrodynamics of turbulent flows in chemically reacting systems, the Reynolds number $\mathrm{Re} = UL/\nu$ expressed in terms of the characteristic velocity U of the gas, linear scale of the system L (combustion-chamber size, pore size, etc.), and kinematic viscosity ν of the gas is used. However, in modeling of turbulent combustion, characteristics related directly to the phenomenon of turbulence are more suitable. Turbulent processes are characterized by the existence of a continuous spectrum of length scales and its associated energy cascade of turbulence [11, 12]. Large length scales (macroscales L_t) correspond to the largest vortices that are practically independent of the action of viscosity and in whose motion the main portion of the turbulent kinetic energy $k = \frac{1}{2}(\overline{u_1^2} + \overline{u_2^2} + \overline{u_3^2})$ is contained. Such energy-containing vortices are unstable, and their inertial interaction and an increasing action of the viscous dissipation $\varepsilon = \overline{\frac{\partial u_i}{\partial x_j} \cdot \frac{\partial u_i}{\partial x_j}}$ bring about vortices with a smaller spatial scale (as small as the Kolmogorov scale η). For them, the molecular effects are governing and their kinetic energy dissipates to the heat energy.

The macroscale or integral scale of turbulence L_t is expressed in terms of the spatial correlations of the flow-velocity pulsations

$$L_t = \int_0^\infty R_{11}\,(x_l, \Delta x_l)\, d\,(\Delta x_l)\,, \tag{1}$$

where $R_{11}(x_l, \Delta x_l)$ is the correlation coefficient of the velocity pulsations in the direction of the flow at the points x_l and $x_l + \Delta x_l$.

The correlation coefficient R_{11} characterizes the gas-dynamic interrelations at the points x_l and $x_l + \Delta x_l$ [12]:

$$R_{11}(x_l;\Delta x_l) = \overline{u_1(x_l)\,u_1(x_l+\Delta x_l)} \Big/ \left[\overline{u_1^2(x_l)}\;\overline{u_1^2(x_l+\Delta x_l)}\right]^{1/2} . \tag{2}$$

It is obvious that $R_{11} \to 0$ for $\Delta x_l \to \infty$, i.e., the macroscale is a measure of the largest connectivity distance (or correlation) of the velocity field.

For a universal description of the degree of turbulence of the flow, the turbulent Reynolds number expressed in terms of the integral length scale has been proposed:

$$\mathrm{Re}_t = u' L_t / \nu , \quad u' = \sqrt{\frac{\overline{u_i u_i}}{3}} = \sqrt{\frac{2}{3}\,k} , \quad i = 1, 2, 3 , \tag{3}$$

where u' is the root-mean-square value of the turbulent velocity pulsations. It is used as the velocity scale and can be interpreted as the velocity of revolution of large vortices [12]. Thus, the number Re_t is directly related to the structure of turbulence in the flow in contrast to Re, which is explicitly dependent on the geometric parameters of the system L. Since the idea of cascade transfer suggests that the evolution of large energy-containing vortices is determined by their inertia and by the viscous dissipation [12], a dimensional analysis shows that their characteristic length and time scales can be expressed in terms of u' and ε:

$$L_t = u'^3 / \varepsilon \quad \text{and} \quad \tau = u'^2 / \varepsilon = L_t / u' . \tag{4}$$

Along with the macroscale, the Kolmogorov microscale η is introduced as a characteristic of the smallest size of vortices responsible for the dissipation of the kinetic turbulent energy. Its diagnostics variables are the kinematic viscosity ν and the dissipation rate of the kinetic turbulent energy ε. It follows from the dimensional analysis [12] that

$$\eta = (\nu^3/\varepsilon)^{1/4} . \tag{5}$$

The corresponding characteristic time and velocity of a Kolmogorov-scale vortex are as follows:

$$\tau_K = (\nu/\varepsilon)^{1/2} , \quad v_K = (\nu\varepsilon)^{1/4} . \tag{6}$$

Let us consider the characteristic linear scales associated with laminar structures in reacting media. This above all is the thickness of the laminar flame in a combustible mixture mixed in advance l_t that is determined by means of the relation $V_f l_f = \nu$, where V_f is the normal laminar velocity of the flame. Based on the value of l_f, we can predict the structure of the turbulent flow of reacting components. For $l_f < \eta$, laminar flames with a pronounced front can exist, while for $L_f < l_f$ the chemical-reaction region is distributed throughout the gas volume. The dynamics of the change in the curvature of the front of the laminar flame in a turbulent flow and its contraction and extension also influence the structure of the turbulent combustion. Excessive extension of the laminar flame due to the velocity gradients can lead to a local suppression of the reaction [13]. Klimov and Williams [14, 15] have formulated a criterion, according to which, in order that the laminar structure of the flame in a turbulent flow be maintained, the thickness of the flame must be smaller than the Kolmogorov scale η. This regime is described using the dimensionless Karlovitz number Ka = τ_{ch}/τ_K, where τ_{ch} is the characteristic time required for the chemical reaction to occur. It can be determined from the ratio $\tau_{ch} = l_f/V_f$.

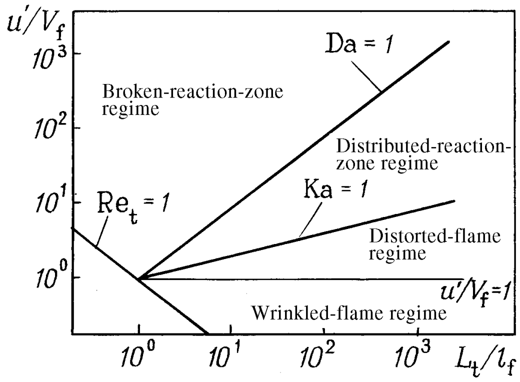

Fig. 1. Borghi diagram for the regimes of turbulent combustion of gases.

The Damköhler number Da = τ/τ_{ch} characterizes the relative rapidity (rate) of the chemical reaction as compared to the processes of turbulent transfer. Large values of Da correspond to a rapid-chemistry condition under which reactions occur in thin curved layers moving in a turbulent flow. For small Da, the rate of the reaction is comparatively low and the turbulent mixing has time to occur before the reaction. Hence, if the time of the chemical reaction τ_{ch} is shorter than the time of the turbulent mixing τ, the chemical processes essentially do not depend on the turbulent-flow field. Otherwise, for $\tau_{ch} > \tau$, the hydrodynamics of the flow influences the rate of the chemical reaction and the structure of the flame.

Classification of the Regimes of Turbulent Combustion of Reagents Mixed in Advance. A classification of turbulent-combustion regimes by the length scales, the degree of turbulence, and other parameters has been performed by a number of research groups [7–9]. Borghi [7] has proposed a diagram, shown in Fig. 1, which divides the range of turbulent-combustion parameters into four subranges corresponding to different combustion regimes. The axis of ordinates is given by the ratio of the value of the velocity pulsations to the velocity of the normal laminar flame u'/V_f, and the axis of abscissas is given by the ratio L_f/l_f. The first regime, called the wrinkled-flame regime, is realized at low-intensity velocity pulsations $u' < V_f$. It satisfies the Damköhler model [10], where the flame-front width is small as compared to the hydrodynamic scales and the turbulence forms the "wrinkled" structure of the front. An increase in the intensity of the pulsations leads to a disturbance of the reaction zone by vortices having a characteristic velocity u'. This situation corresponds to the second regime, called the distorted-flame regime. It is limited by the condition Ka = 1. The above-mentioned regimes satisfy the Klimov–Williams criterion [14, 15] and form the so-called flamelet region. The concept of flamelets was described for the first time in [16] and developed in a number of papers, for example, in [8]. In the latter, the turbulent flame is considered as an ensemble of thin one-dimensional reaction zones (flamelets) transferred by a flow; the reacting elements are bent and stretched by turbulent vortices. It is suggested that flamelets exist individually and their structure can be identified and analyzed. This approach allows one to separate the description of the complex chemistry and the molecular transfer occurring in the reaction zone from the description of the turbulent flow.

According to Borghi, for Ka > 1, the chemical-reaction zone ceases to be thin and widens. In this case, the Klimov–Williams condition is not fulfilled. Such a regime is called the distributed-reaction-zone regime; it is limited by the Damköhler number Da = 1. In this case, the time scale of a chemical reaction is rather small and it may be suggested that reactions are independent of the gas-dynamics of the flow. The smallest vortices can enter the heating and the reaction zones, since $\eta < l_f$, and cause a large distortion of the flame. Hence, a fairly intense turbulence can cause the subdivision of the flame front into individual regions and lead to the cessation of combustion in some of them.

For Da < 1, the classical limiting Damköhler case [10], called the broken-reaction-zone regime, is realized. In this regime, all the scales of turbulence are small as compared to the thickness of the laminar

TABLE 1. Variants of Determination of the Integral Scale of Turbulence and the Mean Value of the Velocity Pulsations under Filtration Conditions in an Inert Porous Body

No. of line	L_t	u'
1	$L_t = \frac{4}{6} d_0 m/(1-m)$	u_g
2	$L_t = f(\mathrm{Re}_t, x_i)$	$u_g/\sqrt{2}$
3	$L_t = 0.75\, u_g/(2\pi N_{sh})$	$u_g/\sqrt{3}$

flame. Vortices with dimensions as large as the integral scale of turbulence L_f can cause extinguishing of certain regions of the flame and mix the sites of combustion.

In a number of works, the above-mentioned limits of the regimes were verified based on new measurements of the fine structure of a turbulent flame. Peters [8] has proposed a somewhat different classification of turbulent combustion, considering the so-called thin-reaction-zone regime in which vortices of the scalar-mixing scale penetrate into the heating region but do not disturb the chemical-reaction zone. In our opinion, the Borghi concept is simpler and physically more transparent. Because of this, it is more suitable for the purposes of our investigation.

Determination of Parameters for the Case of Filtration Combustion. As has been shown above, turbulent combustion can be characterized by eight parameters: integral scale of turbulence L_t, mean-square value of the velocity pulsations u', Kolmogorov scale η, kinematic viscosity of the mixture ν, time of the chemical reaction τ_{ch}, integral and Kolmogorov time scales τ and τ_K, and normal laminar velocity of the flame V_f. The quantities ν, τ_{ch}, l_f, and V_f are the thermophysical and chemical characteristics of the gas mixture and therefore cannot be dependent on the gasdynamic and other conditions of combustion. The Kolmogorov scale η can be found from the ratio $L_f/\eta = \mathrm{Re}_t^{3/4}$ for known Re_t and L_t. Thus, two independent parameters – the integral scale of turbulence L_t and the value of the velocity pulsations u' – determine the formal relation between the turbulent and the filtration combustion.

To determine L_t in accordance with (1), it is necessary to have exact information on the space-time distribution of the filtration field, which, in all probability, will not be obtained in the visible future. The simplest characteristic of the integral scale can be an equivalent hydrodynamic diameter of pores (line 1 in Table 1). At present, there are a number of experimental and theoretical works [4, 5] in which the velocity fields are determined and the integral scale is estimated. It should be noted that the latter is a function of Re_t and of the coordinate (line 2 in Table 1). Unfortunately, the authors have no information on the corresponding changes in the region of $\mathrm{Re}_t \sim 50$–100 that is of greatest interest to us. One more method of determining L_t is to use of the Lawrence estimate [4], according to which the integral scale is expressed is terms of the wave number of the spectral maximum of the pulsations. In this case, the maximum of the pulsation spectrum can be derived experimentally, from acoustic measurements, or obtained on the basis of the model of Strouhal frequencies in a porous medium (line 3 in Table 1).

The simplest estimate of the root-mean-square value of the velocity pulsations is the mean rate of Darcy filtration. There are models of filtration which give other estimates. For example, if we assume that in the main volume of pores the velocity is given by the function $\mathbf{u} = \mathbf{i}u_g(1 + \sin(w't)) + \mathbf{j}u_g \sin(w''t) + \mathbf{k}u_g \sin(w'''t)$, having found $u' = ((\overline{u_1^2} + \overline{u_2^2} + \overline{u_3^2})/3)^{1/2}$, we obtain $u' = u_g/\sqrt{2}$. The model of a gas particle isotropically wandering with a velocity u_g gives the value of the pulsations $u' = u_g/\sqrt{3}$. It should be noted that the investigations of dispersion diffusion point to the inequality of the longitudinal and transverse directions of motion of gas particles [17]. We know the works in which the value of the pulsations was measured experimentally [4, 5, 18]. Unfortunately, the data of these works do not cover the range of Re_t values which are of interest to us and therefore must be considered as estimative.

TABLE 2. Calculation of the Turbulent Characteristics for the Filtration Combustion of Gases (No. is the number of the experiment in the corresponding work)

Position in Fig. 2, reference	φ	P, atm	$D_{por}\cdot 10^3$, m	u', m/sec	T_{max}, K	Re_t	$\tau_{ch}\cdot 10^5$, sec	V_f, m/sec
1, [19], No. 1	0.68	1	1.55	3.73	1935	48	0.99	0.23
2, [19], No. 5	0.56	1	1.55	6.63	2352	64	0.29	0.47
3, [20], No. 4	0.77	6	2.22	0.87	1916	97	1.3	0.138
4, [20], No. 9	0.94	6	2.22	3.8	2126	363	0.58	0.228
5, [20], No. 15	1.06	6	2.22	3.2	2126	306	0.58	0.245
6, [21], No. 1	0.87	1.5	2.22	3.51	1917	97	1.3	0.16
7, [21], No. 7	0.87	2.5	2.22	1.37	2047	58	0.78	0.16
8, [21], No. 7	0.87	2.5	2.22	1.62	1917	75	1.3	0.12

At the moment, it is beyond reason to use one or another complex function for description of the quantities L_t and u' (it is probable that such expressions will be expedient if reliable experimental and calculated data appear). Thus, the main dimensionless parameters of turbulent combustion can be expressed in terms of the filtration-combustion parameters, as is shown in Table 1.

As distinguished from free jets, the value of the pulsations u' in filtration combustion is determined by the rate of filtration relative to the skeleton. In this case, depending on the gas-supply regime, the velocity of motion of combustion products u_b relative to the skeleton can be higher or lower than u_g. In particular, there can exist regimes in which $u_g = 0$ and $u_b \neq 0$ and conversely. Because of this, rules of determining the characteristic rate of filtration in the combustion region are necessary. For this rate we take the mean of the absolute values of the gas and the combustion product velocities relative to the porous medium $u' = (|u_b| + |u_g|)/2$. To maintain the internal consistency of the model, in calculations of Re_t the viscosity is taken for the temperature averaged over the front $(T_{max} + T_0)/2$.

Examples of Classification of Filtration-Combustion Regimes. To show how the model of turbulent-filtration similarity can be used, we calculate the "turbulent" characteristics for a number of cases of filtration combustion of gases [19–21] (Table 2). It is important to keep in mind when performing estimations that the dynamics and temporal parameters of combustion must be calculated for the conditions realized in the flame front. In the low-rate regime of filtration combustion ([19] and experiment No. 1 in [21]), super- or subadiabatic temperatures are realized in the flame front. These temperatures must form the basis for calculations of the characteristic time of the chemical reaction τ_{ch} and the normal laminar velocity of the flame V_f. Two experiments in [19] concern the low-rate regime in which the temperature profiles of the gas and the skeleton are closely related to each other. In this case, we had a wake propagation of the wave and, correspondingly, a superadiabatic temperature in the front, calculated from the formula $\Delta T_{max} = \Delta T_{ad}/(1 - u)$. In the experiments in [20], the high-rate regime of combustion was realized. In this regime, the temperatures of the gas and the skeleton were substantially independent; therefore, the maximum temperature in the front was estimated as adiabatic for the given mixture, and the velocity V_f was taken from [20]. The distinctive properties of the investigation in [20] were that the combustion occurred in a closed tube without forced filtration. To construct the criterion Re_t it is necessary to determine the hydrodynamic velocity (filtration rate) of a cold gas before the combustion front. With the aim of determining this quantity, the problem of the rate of change of the volume of the ideal-gas initial mixture has been solved for the case of a constant rate of combustion relative to the cold gas at rest and direct proportionality between the pressure in the system and the mass of the burnt mixture. The solution of the problem presents no significant difficulties and is omitted here. This solution has shown that in a fairly wide range of parameters characteristic of the experiments in [20] the filtration rate is approximately a constant part of the observed velocity of propagation of the flame $u_g \approx 0.7S$. With the use of this relation and the data from [20], the corresponding values of Re_t have been found from

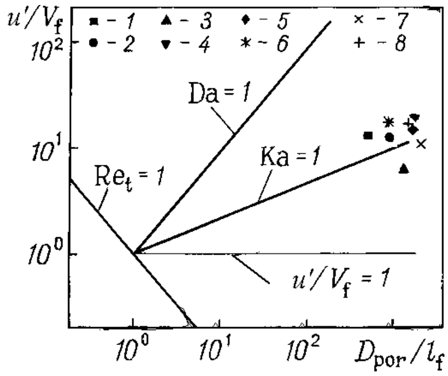

Fig. 2. Borghi diagram for the filtration combustion of gases. The symbols point to the cases presented in Table 2.

the observed velocity *S*. The first of the considered experiments [21] is similar to [19], but in it the subadiabatic regime of filtration combustion (counterpropagation of the combustion front) is realized. The second experiment concerns the boundary regime in which a small change in the parameters (pressure in this case) leads to a jump of the flame, i.e., the high-rate regime is realized. Table 2 presents the characteristics calculated for the high-rate and low-rate regimes. In all the cases, the time of chemical transformation τ_{ch} was calculated from the formula [13]

$$1/\tau_{ch} = k_0 \left(a_0 \rho_b\right)^{n-1} \exp\left(-E/RT_b\right) . \tag{7}$$

The rate of the normal laminar combustion in the given mixture at a given pressure was calculated, except for the experiments in [20], in accordance with [13]:

$$V_f = \left(\frac{2n\,!}{\left(E\left(T_{max} - T_0\right)/RT_{max}^2\right)^{n+1}} \frac{\kappa\rho_b^2}{\tau_{ch}\,\rho_0^2} \right)^{1/2} ; \tag{8}$$

use was made of the Arrhenius kinetics of first order [22]: k_0 = 2.6·10^8 1/sec and E = 130 kJ/mole, which satisfies the experimental data on the velocity of the normal laminar flame.

Using the calculated parameters of the filtration combustion presented in Table 2, we construct a diagram similar to the Borghi diagram for the turbulent combustion. The axis of ordinates will be given by the ratio of the mean rate of filtration u' to the velocity of the normal laminar flame V_f, and the axis of abscissas will be given by the ratio of the equivalent size of the pores D_{por} to the width of the laminar flame $l_f = V_f\tau_{ch}$. The Reynolds number was calculated in terms of D_{por} and u': $\mathrm{Re}_t = D_{por}u'/\nu$, where ν is the kinematic viscosity of the gas. The numbers Da and Ka were introduced similarly to the case of turbulent combustion.

As is obvious from the diagram in Fig. 2, the considered experimental data correspond to the distorted-flame regime and the distributed-reaction-zone regime. In accordance with the idea of the present work, it may be suggested that the condition for the flamelet description of the flame structure is realized in the third and seventh considered cases of filtration combustion [8, 23–27], the distributed-reaction-zone regime is realized in the first and sixth cases, and the boundary regimes are realized in the other considered cases.

In investigating the velocity of propagation of the front in the distorted-flame and distributed-reaction-zone regimes [27], the following formulas are respectively recommended:

$$u_t/V_f \approx \mathrm{Re}_t^{1/4} \exp\left(0.4\left(u'/V_f\right)^{1/2}\right) \tag{9}$$

$$u_t/u' \sim (V_f/u')^{3/4} \qquad (10)$$

One can also find other expressions in the literature. It should be noted that formulas similar to (9) and (10) do not give the actual rate of filtration combustion, since the interphase heat transfer will affect its value as soon as the interphase heat fluxes become comparable to the fluxes in the combustion and heating zones. But the velocity of propagation of the flame u_t will form a part of the model of filtration combustion, the consideration of which is beyond the scope of the present paper. Moreover, this quantity determines the upper limit of the combustion rate in separation of the gas-phase flame from the skeleron (high-rate regime).

Discussion. An important result of the analysis performed is the conclusion that the gas-phase combustion is flamelet in character in a number of characteristic cases of filtration combustion, including high-rate regimes. This means that, under the given conditions, the zone of chemical heat release has a width much smaller than the pore size and forms a combustion surface (plate) continuous in the volume of the system and well-resolved at every instant of time. It follows, in particular, that some results of the experimental measurement of the reaction-zone width [28] must be interpreted differently than in [28]. For example, the width of the chemical-reaction zone, observed from the luminescence of the open channel, is determined not (or not only) by its increase, but by the spatial dispersion of individual regions of the flame plate. This supposition can easily be verified experimentally. To do this, it is necessary to carry out a number of experiments similar to [28], but with reaction tubes different in diamater. If the measured width is the same for different tubes, it is due to the widening of the heating and reaction zones. If larger diameters correspond to a larger width, it is due to the spatial dispersion of individual regions of the flame.

On the other hand, the majority of characteristic cases of filtration combustion can be characterized as boundary between the flamelet and the broken-reaction-zone regimes. This conclusion is important from the viewpoint of substantiation of the model of the change from the low-rate regime to a high-rate one [21] and for analysis of the conditions for quenching of the flame in filtration combustion. For example, in analysis of the limit of propagation of the flame in the high-rate regime [21] and in the theory of a transient regime [21], the characteristic length and time of quenching of the front are determined from the cooling of the front within the time interval $\Delta T = RT_b^2/E$. This limit has been derived for normal laminar flames [13] and its use for regimes with a distorted front or distributed reaction zones requires additional substantiation. In view of the results obtained, the model of the transient regime of filtration combustion must be modified so as to take into account a decrease in the characteristic temperature interval of quenching in accordance with the combustion regime.

Conclusions. It has been suggested in the work that the processes of turbulent and filtration combustion can be considered as analogous from the viewpoint of the processes of chemical kinetics, mixing, and formation of the flame structure. In this case, two quantities – the integral scale of turbulence and the root-mean-square value of the velocity pulsations – are independent parameters, using which one can establish a correspondence between the processes of turbulent and filtration combustion. It is shown that in a number of cases of filtration combustion, including the high-rate regime, the conditions for the flamelet structure of the flame (distorted-flame regime) are realized, but the majority of characteristic cases of filtration combustion can be characterized as combustion regimes with distributed reaction zones or as boundary regimes relative to the above-mentioned regimes. This allows one to use the experience in describing turbulent combustion for solution of urgent problems of filtration combustion of a gas.

The immediate continuation of this work can be experimental refinement of the turbulent characteristics of filtration combustion, for example, by acoustic methods, and construction of a quantitative model of the high-rate regime and the transient regime of filtration combustion of gases.

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NOTATION

u_i, orthogonal components of velocity pulsations; x_i, spatial coordinates; u_g, mean rate of filtration of the initial gas mixture; w', w'', and w''', quasiconstant frequencies; ΔT_{ad}, adiabatic increase in the temperature as a result of burning of the combustible mixture; $u = u_w/u_h$, dimensionless ratio of the velocity of motion of the filtration-combustion front to the heat-wave velocity in the absence of combustion; S, observed velocity of propagation of the flame; ρ_b, density of the combustion products; ρ_0, density of the initial gas; a_0, initial concentration of the reagents; n, order of reaction; k_0, preexponent of the chemical-reaction rate; E, activation energy of the reaction; R, universal gas constant; T_b, temperature of the combustion products; T_{max}, maximum temperature in the filtration-combustion wave; T_0, initial gas temperature; κ, thermal diffusivity of the combustion products; ΔT, temperature interval; d_0, diameter of the charge particles; m, porosity; N_{sh}, Strouhal frequency; P, pressure; φ, equivalence ratio for a gas mixture. Subscripts: i, j, and l, vector components; b, combustion products; w, filtration-combustion wave in the low-rate regime; h, heat wave in the absence of combustion.

REFERENCES

1. Yu. Sh. Matros, *Propagation of Heat Waves in Heterogeneous Media* [in Russian], Novosibirsk (1988).
2. S. A. Zhdanov, V. V. Martynenko, and S. I. Shabunya, *Inzh.-Fiz Zh.*, **64**, No. 5, 569–576 (1993).
3. G. A. Fateev and O. S. Rabinovich, in: *Proc. 27th Int. Symp. on Comb.*, The Combustion Institute, Pittsburgh, PA (1998), pp. 2451–2458.
4. D. F. Van der Merwe and W. H. Gauvin, *AIChE J.*, **17**, No. 3, 519–528 (1971).
5. H. S. Mickley, K. A. Smith, and E. I. Korchak, *Chem. Eng. Sci.*, **20**, 237–246 (1965).
6. A. A. Zhakauskas, *Heat Transfer in Tube Bundles* [in Russian], Kaunas (1980).
7. R. Borghi, *Prog. Energy Combust. Sci.*, **14**, 245–292 (1988).
8. N. Peters, in: *Proc. 21st Int. Symp. on Comb.*, The Combustion Institute, Pittsburgh, PA (1986), pp. 1231–1250.
9. V. L. Zimont, in: *MCS-99 Proc.*, Antalia, June (1999), pp. 1155–1165.
10. G. Damköhler, *Z. Elektrochem.*, **46**, 601–626 (1940).
11. L. G. Loitsyanskii, *Mechanics of Liquids and Gases* [in Russian], Moscow (1978).
12. J. O. Hinze, *Turbulence. An Introduction to Its Mechanism and Theory* [Russian translation], Moscow (1963).
13. Ya. B. Zel'dovich, G. I. Barenblatt, V. B. Librovich, and G. M. Makhviladze, *Mathematical Theory of Combustion and Explosion* [in Russian], Moscow (1980).
14. A. M. Klimov, *Zh. Prikl. Mekh. Tekh. Fiz.*, No. 3, pp. 49–58.
15. F. A. Williams, *Comb. Flame*, **26**, 269–270 (1976).
16. F. A. Williams, in: S. N. B. Murty (ed.), *Turbulent Mixing in Non-Reactive and Reactive Flows* (1975), pp. 189–208.
17. M. É. Aérov, O. M. Todes, and D. A. Narinskii, *Apparatuses with a Stationary Granular Bed* [in Russian], Leningrad (1979).
18. V. S. Babkin, V. I. Drobyshevich, Yu. N. Laevskii, and S. I. Potytnyakov, *Fiz. Goreniya Vzryva*, No. 2, 17–26 (1983).
19. K. V. Dobrego and S. A. Zhdanok, *Int. J. Heat Mass Transfer*, **44**, No. 11, pp. 2127–2136 (2001).
20. V. S. Babkin, A. A. Korzhavin, and V. A. Bunev, *Comb. Flame*, **87**, 182–190 (1991).
21. K. V. Dobrego, S. A. Zhdanok, and E. I. Khanevich, *Exp. Thermal Fluid Sci.*, **21**, 9–16 (2000).
22. K. Hanamura, R. Echigo, and S. Zhdanok, *Int. J. Heat Mass Transfer*, **36**, No. 13, 3201–3209 (1993).
23. S. K. Liew, K. N. C. Bray, and J. B. Moss, *Combust. Sci. Technol.*, **27**, 69–73 (1981).

24. W. T. Ashurst, in: *Proc. 25th Int. Symp. on Comb.*, The Combustion Institute, Pittsburgh, PA (1995), pp. 1075–1089.
25. S. B. Pope, in: *Proc. 23rd Int. Symp. on Comb.*, The Combustion Institute, Pittsburgh, PA (1990), pp. 591–612.
26. P. A. Libby and F. A. Williams, *Turbulent Reacting Flows*, New York (1994).
27. O. L. Gulder, in: *Proc. 23rd Int. Symp. on Comb.*, The Combustion Institute, Pittsburgh, PA (1990), pp. 743–750.
28. A. A. Korzhavin, V. A. Bunev, R. Kh. Abdullin, and V. S. Babkin, *Fiz. Goreniya Vzryva*, No. 6, 20–23 (1982).