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TRANSFER PROCESSES IN POROUS MEDIA

ON THE INFLUENCE OF DIFFUSION-THERMAL EFFECTS ON THE DEVELOPMENT OF PERTURBATIONS OF THE FILTRATION COMBUSTION FRONT OF GASES

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It has been shown that the filtration combustion front of gases is resistant to small perturbations at any asymmetry between the diffusion and thermal transport. A qualitative analysis of the perturbation development with time confirming that the diffusion-thermal asymmetry does not influence the front stability has been carried out.

The combustion of gases in a porous medium or the filtration combustion of gases (FCG) that occurs widely in nature finds application in cleaning air, free-flowing materials, and sorbents from organic pollutants [1], in thermochemical conversion of hydrocarbons [2, 3], in recovery of low-calorie gaseous fuels [4, 5], etc.

In designing and using devices for filtration combustion, the question of FCG stability is important. Practice shows that in low-calorie mixture reactors a deformation of the front may arise and its integrity may be disturbed [6], and also the geometry of filtration combustion fronts moving concurrently with the flow is easily changed [7, 8]. The authors of the above-cited works have established that the main mechanism controlling the dynamics of perturbations is hydrodynamic — concurrent proceeding and competition of the processes of redistribution of filtration flows enhancing the thermal inhomogeneities of the combustion front and conductive relaxation of the front inhomogeneities. Experiments show that in a methane–air mixture long-wave perturbations, in particular, front-tilt perturbations, have the highest growth rate.

Under combustion of impoverished hydrogen–air mixtures a specific kind of FC front perturbations takes place — the so-called site instability that shows up as a fragmentation of the front and the formation of individual spherical combustion sites. For instance, in [9] the formation of multiple sites under filtration combustion of a hydrogen–air mixture at a hydrogen concentration of 4–7% is described. In [10], the formation of sites in a poor hydrogen–air mixture with very low temperatures (~900 K) was noted. The mechanism of the formation of such structures has not yet been explained, while the most probable mechanism under growth and stabilization of short-wave (site) perturbations acting when the number $\mathrm{Le} = D/\kappa$ considerably exceeds unity is accepted to be the diffusion-thermal mechanism [9]. (This type of instability for normal laminar flames has been analyzed by the method of small perturbations by B. Ya. Zeldovich and other scientists [11–13].)

In the present paper, the influence of the diffusion-thermal transfer asymmetry on the FCG front stability has been investigated and it has been shown that this asymmetry does not play the decisive role in the formation of perturbations.

The mathematical problem on filtration combustion is formulated as a system of heat and mass balance equations for the solid and gas phases jointly with filtration and state equations for gas [14]. In the one-temperature approximation (the interphase heat-transfer coefficient $\alpha_V \to \infty$) under the condition $u_g >> u_w$, $\rho_s >> \rho_g$ the system of FCG equations can be written in the following form:

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$$\frac{\partial T}{\partial t} = -\tilde{u}\frac{\partial T}{\partial x} + \tilde{\kappa}\left(\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2}\right), \tag{1}$$

$$\frac{\partial a}{\partial t} = -u_g\frac{\partial a}{\partial x} + \tilde{D}\left(\frac{\partial^2 a}{\partial x^2} + \frac{\partial^2 a}{\partial y^2}\right). \tag{2}$$

Here $\tilde{u} = u_{th}(1-\bar{u}_w)$; $\tilde{\kappa} = \frac{\tilde{\lambda}}{c\rho} = \frac{\lambda_s + \tilde{\lambda}_g}{c_s\rho_s}$, the y- and x-axes are directed along the front and perpendicular to it; to the positive and negative values of x corresponds the position after and before the front.

Compared to the system of equations for the gas-phase flame [12], system (1)–(2) contains the specific coefficients $\tilde{u}$ and $\tilde{\kappa}$ and the dispersion gas diffusion and heat-conductivity coefficients. For the characteristic values of parameters ($\bar{u}_w = 0.5$, $u_g = 0.5$ m/sec, $u_{th} = 10^{-3}$ m/sec, $\lambda_s = 1$ W/(m·K), $\tilde{D}_g = 5\cdot10^{-4}$ m^2/sec, $\tilde{\lambda}_g = 0.5$ W/(m·K) the values of the coefficients are: $\tilde{u} \approx 5\cdot10^{-4}$ m/sec, $\tilde{\kappa} \approx 1.5\cdot10^{-6}$ m^2/sec, and the concentration and thermal thicknesses of the stationary wave front $\delta_D \approx 10^{-3}$ m and $\delta_\lambda \approx 3\cdot10^{-3}$ m.

Using the method of small perturbations analogously to [12], let us show that, on the assumption of a high activation energy of the chemical reaction, the combustion front is stable whatever the Lewis number.

Consider the chemical reaction zone as a weak discontinuity surface on which the concentrations and temperatures of components are continuous and the flows have a discontinuity. The matching conditions as to the concentration, temperature, and flow of matter are of the form

$$a\big|_{x_f-0} = a\big|_{x_f+0}\,, \quad T\big|_{x_f-0} = T\big|_{x_f+0}\,, \quad m = \rho_g\tilde{D}\frac{\partial a}{\partial n}\bigg|_{x_f+0} - \rho_g\tilde{D}\frac{\partial a}{\partial n}\bigg|_{x_f-0}\,.$$

Since the component is expended completely ($a(x > x_f) \equiv 0$), the latter condition will be written as $m = -\rho_g\tilde{D}\frac{\partial a}{\partial n}\Big|_{x_f-0}$. The dependence of the amount of matter burnt up per unit time on the front temperature T_f is as follows (this follows from the consideration of the structure of the chemical reaction zone):

$$m \sim \exp\left(-\frac{E}{2RT_f}\right).$$

Another boundary condition is the energy conservation law

$$\tilde{\lambda}\left(\frac{\partial T}{\partial n}\bigg|_{x_f+0} - \frac{\partial T}{\partial n}\bigg|_{x_f-0}\right) + Q\rho_g\tilde{D}\left(\frac{\partial a}{\partial n}\bigg|_{x_f+0} - \frac{\partial a}{\partial n}\bigg|_{x_f-0}\right) = 0\,,$$

as in [12]. However, such a form of writing subsequently leads to awkward expressions. Therefore, as an additional condition, we used the energy-conservation equation for the quasi-stationary FCG wave in the form $\frac{\Delta T_{ad}}{\Delta T_{max}} = 1 - \bar{u}_w$, where $\Delta T_{max} = T_f - T_0$.

Let us write the unperturbed equation as

$$T_1^{(0)} = T_0 + \left(T_f^{(0)} - T_0\right)\exp\left(\frac{x\tilde{u}}{\tilde{\kappa}}\right), \quad T_2^{(0)} = T_f^{(0)}\,, \quad a_1^{(0)} = a_0\left(1 - \exp\left(\frac{xu_g}{\tilde{D}}\right)\right), \quad a_2^{(0)} = 0\,.$$

Here and hereinafter, subscripts 1 and 2 pertain to the region before and after the front, respectively.

The perturbed distributions for the temperatures and concentrations (except for the concentration after the wave front) are made up of unperturbed solutions and perturbations:

$$T_1 = T_1^{(0)} + T_1', \quad T_2 = T_2^{(0)} + T_2', \quad a_1 = a_1^{(0)} + a_1', \quad a_2 = 0,$$

where

$$T_1' = g\left(T_{\mathrm{f}}^{(0)} - T_0\right)\exp\,(b_1 x + iky + \omega t)\,;$$

$$T_2' = h\left(T_{\mathrm{f}}^{(0)} - T_0\right)\exp\,(-\,b_2 x + iky + \omega t)\,;$$

$$a_1' = f a_0 \exp\,(b_3 x + iky + \omega t)\,.$$

Here the signs before positive coefficients b_j were chosen so that at a distance from the flame front perturbations attenuate.

Substituting the perturbed solutions for T_1, T_2, and a_1 into the heat-conduction and diffusion equations, we obtain the following equations for coefficients b_j:

$$\omega = -\,\tilde{u} b_1 + \tilde{\kappa}\,(b_1^2 - k^2)\,, \quad \omega = \tilde{u} b_2 + \tilde{\kappa}\,(b_2^2 - k^2)\,, \quad \omega = -\,u_{\mathrm{g}} b_3 + \tilde{D}\,(b_3^2 - k^2)\,.$$

Hence

$$b_{1,2} = \pm\frac{\tilde{u}}{2\tilde{\kappa}} + \sqrt{\frac{\tilde{u}^2}{4\tilde{\kappa}^2} + k^2 + \frac{\omega}{\tilde{\kappa}}}\,, \quad b_3 = \frac{u_{\mathrm{g}}}{2\tilde{D}} + \sqrt{\frac{u_{\mathrm{g}}^2}{4\tilde{D}^2} + k^2 + \frac{\omega}{\tilde{D}}}\,.$$

The perturbed front profile is regarded as a y-periodic and time exponential perturbation: $x_{\mathrm{f}} = \varepsilon \exp(\omega t + iky)$. Then the matching conditions as to the concentration and temperature upon linearization take the form

$$a_1^{(0)}(0) + \left.\frac{da_1^{(0)}}{dx}\right|_0 x_{\mathrm{f}} + a_1'(0) = a_2(x_{\mathrm{f}}) = 0 \Rightarrow \frac{u_{\mathrm{g}}}{\tilde{D}}\,\varepsilon - f = 0\,,$$

$$T_1^{(0)}(0) + \left.\frac{dT_1^{(0)}}{dx}\right|_0 x_{\mathrm{f}} + T_1'(0) = T_2^{(0)}(0) + \left.\frac{dT_2^{(0)}}{dx}\right|_0 x_{\mathrm{f}} + T_2'(0) \Rightarrow \frac{\tilde{u}}{\tilde{\kappa}}\,\varepsilon + g - h = 0\,.$$

The matching condition as to the flow of matter will be written as

$$\frac{-\,\rho_{\mathrm{g}}\tilde{D}\left.\dfrac{\partial a_1}{\partial n}\right|_{x_1} - \,\rho_{\mathrm{g}}\tilde{D}\left.\dfrac{\partial a_1^{(0)}}{\partial n}\right|_0}{-\,\rho_{\mathrm{g}}\tilde{D}\left.\dfrac{\partial a_1^{(0)}}{\partial n}\right|_0} = \frac{\exp\left(-\dfrac{E}{2RT_{\mathrm{f}}}\right) - \exp\left(-\dfrac{E}{2RT_{\mathrm{f}}^{(0)}}\right)}{\exp\left(-\dfrac{E}{2RT_{\mathrm{f}}^{(0)}}\right)}\,,$$

and upon its linearization as

$$\frac{\left.\dfrac{d^2 a_1^{(0)}}{dx^2}\right|_0 x_{\mathrm{f}} + \left.\dfrac{\partial a_1'}{\partial x}\right|_0}{\left.\dfrac{\partial a_1^{(0)}}{\partial x}\right|_0} = \frac{E}{2R\left(T_{\mathrm{f}}^{(0)}\right)^2}\left(T_{\mathrm{f}} - T_{\mathrm{f}}^{(0)}\right) \Rightarrow \frac{u_{\mathrm{g}}}{\tilde{D}}\,\varepsilon - b_3\frac{\tilde{D}}{u_{\mathrm{g}}} f - zh = 0\,,$$

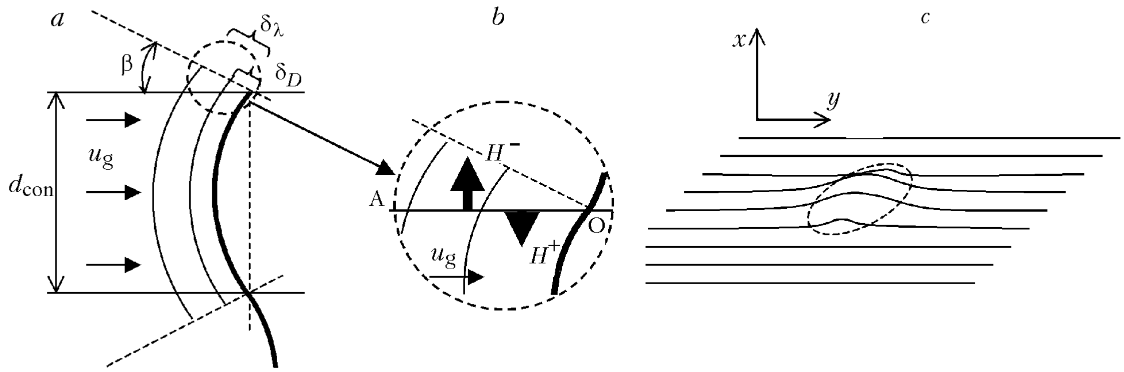

Fig. 1. Scheme of the perturbed portion of the FCG (semibold line denotes the combustion front); a) perturbed part of the FCG front; b) heat transfer through the lateral surface of the part; c) three-dimensional form of perturbation.

where $z = \dfrac{E}{2R(T_f^{(0)})^2}(T_f^{(0)} - T_0)$.

Linearization of the condition $\dfrac{\Delta T_{ad}}{\Delta T_{max}} = 1 - \bar{u}_w$ with account of $\tilde{u} = u_{th}(1 - \bar{u}_w)$ leads to the equation

$$\frac{\omega}{u_{th}\,(1 - \bar{u}_w)}\,\varepsilon - h = 0.$$

As a result, we obtain a homogeneous system of four linear equations for the perturbation amplitude ε, f, g, h:

$$\frac{u_g}{\tilde{D}}\,\varepsilon - f = 0\,,\quad \frac{\tilde{u}}{\tilde{\kappa}}\,\varepsilon + g - h = 0\,,\quad \frac{u_g}{\tilde{D}}\,\varepsilon - b_3\frac{\tilde{D}}{u_g}f - zh = 0\,,\quad h - \frac{\omega}{u_{th}\,(1-\bar{u}_w)}\,\varepsilon = 0\,.$$

Equating the system determinant to zero and substituting into it the expression for b_3, we arrive at the following equation for ω:

$$\frac{u_g}{2\tilde{D}} - \sqrt{\frac{u_g^2}{4\tilde{D}^2} + k^2 + \frac{\omega}{\tilde{D}}} = \frac{\omega z}{u_{th}\,(1-\bar{u}_w)}\,.$$

Evidently, it has no real positive solutions. Consequently, the FCG front is resistant to small perturbations at any asymmetry between the diffusion and thermal transports.

Let us perform an additional qualitative analysis of the diffusion-thermal mechanism of instability of the FCG front without considerable simplifications in the problem formulation.

Let the combustion front be subjected to an insignificant sinusoidal perturbation (Fig. 1). We assume that the filtration field before the front is unperturbed (thermohydrodynamic mechanisms are off). The heat balance of the porous skeleton in the heating region of the considered part of the front determines the velocity of travel of this part. It is formed due to the convective heat transfer to the cold mixture and the conductive heat flux from the heat-release front to the heating region. Let us see how the asymmetry of the diffusion-thermal transport influences this balance.

Since the analog of the Lewis number for the system of FCG equations (1)–(2) is a complex expression, below we shall use the concepts of symmetry ($\delta_D = \delta_\lambda$) and asymmetry ($\delta_D \neq \delta_\lambda$) of the diffusion-thermal transport. At $\delta_D = \delta_\lambda$ the temperature and concentration profiles are similar and perturbations dissipate due to the heat conduction. In the case where $\delta_D \neq \delta_\lambda$, the mechanism of enthalpy redistribution in the combustion front appears. Let us estimate the corresponding effect. Let the convex part of the front be of diameter d_{con} (Fig. 1). Through the lateral surface of the preheating region (OA in Fig. 1), diffusion of the missing component providing enthalpy inflow and conductive heat outflow occur. The above flows can be estimated as

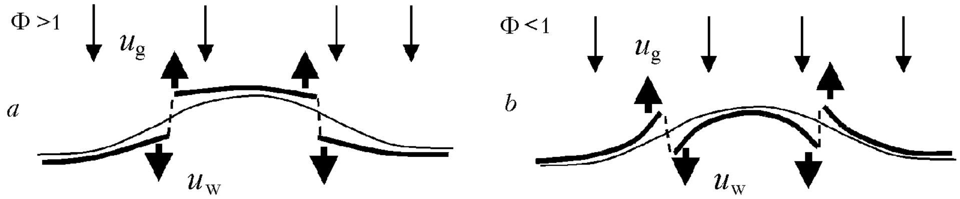

Fig. 2. Character of the evolution of small perturbations (thin solid line) at various Lewis numbers: a) transition of the front to the neutral state at $\Phi > 1$; b) wave-frequency multiplication with decreasing amplitude $\Phi < 1$.

$$H^{+} = h_i\, \rho_g \tilde{D}_g \nabla^{\perp} a S_D\,, \quad H^{-} = \tilde{\lambda} \nabla^{\perp} T S_{\lambda}\,, \tag{3}$$

$\nabla^{\perp} a$ and $\nabla^{\perp} T$ are, respectively, the concentration and temperature gradients in the direction perpendicular to OA. Since $\nabla^{\perp} a \approx (a_0/\delta_D) \sin\beta$, $\nabla^{\perp} T \approx (\Delta T_{\max}/\delta_{\lambda}) \sin\beta$, $S_D \approx \pi d_{\text{con}} \delta_D/\cos\beta$, and $S_{\lambda} \approx \pi d_{\text{con}} \delta_{\lambda}/\cos\beta$, we have

$$H^{+} = h_i\, \rho_g \tilde{D}_g a_0 \pi d_{\text{con}} \tan\beta\,, \quad H^{-} = \lambda \Delta T_{\max} \pi d_{\text{con}} \tan\beta\,. \tag{4}$$

The explicit dependence on the front thickness in (4) is absent, and the total balance determined by the transfer parameters is proportional to the perturbed region diameter and the quantity $\tan\beta$: $\Delta H = H^{+} - H^{-} = \pi d_{\text{con}} (h_i \rho_g \tilde{D}_g a_0 - \lambda \Delta T_{\max}) \tan\beta$. Then the heat excess per unit area of the convex part is

$$\Delta H_{\text{sp}} = \frac{4}{d_{\text{con}}} (h_i\, \rho_g \tilde{D}_g a_0 - \lambda \Delta T_{\max}) \tan\beta\,. \tag{5}$$

Taking as a model of the perturbed part the geometry of a sphere segment with a radius of curvature r_c, we get $d_{\text{con}} = 2 r_c \sin\beta$ and

$$\Delta H_{\text{sp}} = \frac{2}{r_c} \frac{h_i\, \rho_g \tilde{D}_g a_0 - \lambda \Delta T_{\max}}{\cos\beta}\,. \tag{6}$$

Thus, ΔH_{sp} increases with increasing angle β, and in so doing $\Delta H_{\text{sp}} \to \infty$ at $\beta \to \pi/2$. Differentiating (6) with respect to $r_{\text{con}} = r_c \sin\beta$, we obtain the differential excess of heat (source term) in the perturbation cross section, which also turns out to be a monotonically increasing function of β:

$$\frac{d\,(\Delta H_{\text{sp}})}{d r_{\text{con}}} = \frac{2}{r_c^2} \left(h_i\, \rho_g \tilde{D}_g a_0 - \lambda \Delta T_{\max} \right) \frac{\tan\beta}{\cos^2\beta} = \frac{\Delta H_{\text{sp}}}{r_c} \frac{\tan\beta}{\cos\beta}\,. \tag{7}$$

Obviously, heat disbalance takes place at $(h_i \rho_g \tilde{D}_g a_0 - \lambda \Delta T_{\max}) \neq 0$ or $\Phi = \dfrac{h_i \rho_g \tilde{D}_g a_0}{\lambda \Delta T_{\max}} \neq 1$. (Note that the approximation $S_D \approx \pi d_{\text{con}} \delta_D/\cos\beta$ can be replaced by the less crude approximation $S_D \approx \pi d_{\text{con}} \left(\sqrt{r_c^2 \cos^2\beta + 2 r_c \delta_D + \delta_D^2} - r_c \cos\beta \right)$, giving a slower and finite growth of S_D with β. In so doing, however, the character of relation (7) and the conclusion on resistance of the flat front to curvatures are preserved.)

At $\Phi = \dfrac{h_i \rho_g \tilde{D}_g a_0}{\lambda \Delta T_{\max}} > 1$, the curvature of the perturbed part decreases and the front goes to a neutral (stable) state slightly differing from the unperturbed one (Fig. 2a). In the case where $\Phi = \dfrac{h_i \rho_g \tilde{D}_g a_0}{\lambda \Delta T_{\max}} < 1$, as the radius increases, there is an increase in the heat deficiency, and, therefore, the perturbation amplitude of the convex part of the front increases. In so doing, however, the perturbed part as a whole moves into the depth relative to the middle posi-

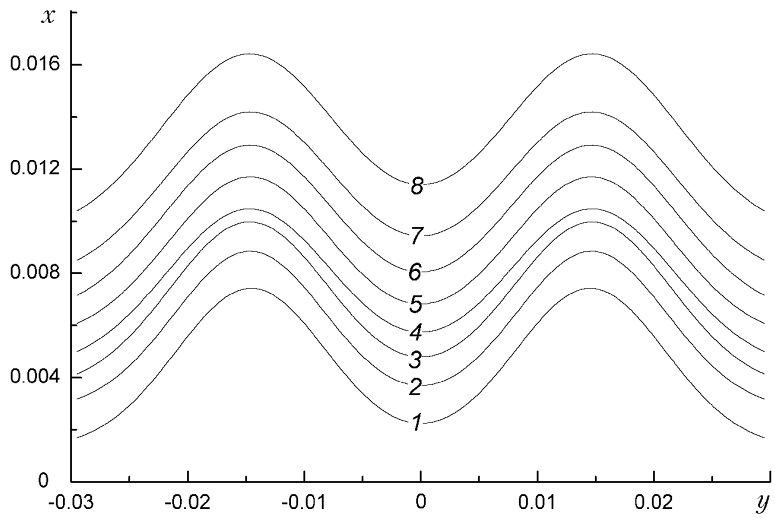

Fig. 3. Temperature field isoline of initial perturbations of the FCG front: 1) T = 400; 2) 500; 3) 600; 4) 700; 5) 800; 6) 900; 7) 1000; 8) 1100 K. x, y, m.

tion of the front (Fig. 2b), wave-frequency multiplication occurs, and there is a general decrease in the amplitude. From the performed analysis of the perturbation evolution the resistance of the front to small perturbations follows.

Note that the criteria characterizing the diffusion-thermal asymmetry for the FCG problem are not connected with the Lewis number constructed by the molecular or dispersion coefficients of transfer in the gas phase. Thus, for poor hydrogen flames Le ~ 3, and in the case of dispersion transfer coefficients $\mathrm{Le_d} \sim 1.3$. Under FCG of poor hydrogen–air mixtures, $\Phi = \dfrac{h_i \rho_g \tilde{D}_g a_0}{\lambda \Delta T_{\max}} \sim 1$.

According to the analysis performed, the diffusion-thermal asymmetry is not an important mechanism of FCG front perturbation. The main mechanism of the appearance of site instability is the thermohydrodynamic one.

The results obtained have been tested by numerical calculations by the following method. We simulated the evolution of the sinusoidal perturbation amplitude of the FCG wave of a poor (equivalent ratio $\varphi = 0.55$) methane–air mixture (Fig. 3). The diameter of the system (and of the calculated domain) is 6 cm, the length is 20 cm, and the diameter of packing particles $d_p = 5$ mm. The initial perturbation amplitude expressed in terms of fractions of the diameter of the perturbed part $\varepsilon/d_{con} = 0.1$. For the calculations we used a detailed two-temperature model. The model, the mathematical formulation, and the solution algorithm are described in [14, 15]. To exclude hydrodynamic factors, the filtration field was a quasi-one-dimensional (the transverse gas flow was excluded).

The time evolution curves of the dimensionless perturbation amplitude are given in Fig. 4. The calculations show that, in the absence of the hydrodynamic redistribution of filtration, the small perturbations decrease by a law close to exponential. In so doing, the first stage of perturbation relaxation ($t < 70$ sec) corresponds to the perturbation relaxation in the near-axis region and the further evolution — to the perturbation relaxation of the scale of the diameter of the whole system. A change in the diffusion coefficient from $0.1D_{air}$ to $3D_{air}$ (at a constant heat conductivity of the gas) practically does not influence the relaxation dynamics of the initial perturbation. As the diffusion coefficient increases to $10D_{air}$, the perturbation relaxation rate decreases. This is due to the fact that in the gas phase perturbations arise, whose nature apparently corresponds to the classical diffusion-thermal instability of the gas-phase flame. It should be noted that because of the heat exchange with the porous skeleton the amplitude of perturbations in the gas phase stabilizes at a rather low level and does not lead to perturbations in the gas–porous medium system. Note that a tenfold excess of the diffusion coefficient over the diffusion coefficient of methane in air does not occur in the practically realized reaction systems.

Thus, in the present paper, a complex analysis of the influence of thermodiffusion asymmetry in the gas phase on the FCG front stability has been carried out. It has been shown that the diffusion-thermal disbalance does not lead to a growth of perturbations but in some cases can produce an effect on the quantitative characteristics of the growth or relaxation of perturbations. In so doing, the thermohydrodynamic mechanism is probably dominant in the case of

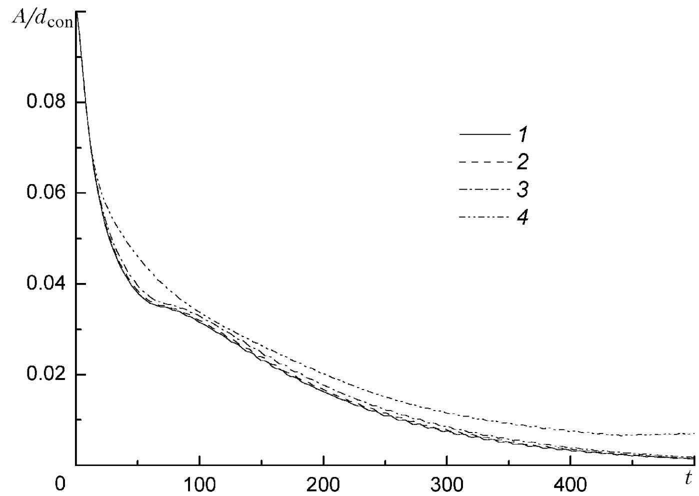

Fig. 4. Time dependence of the dimensionless perturbation amplitude A/d_k of the plane FCG wave in the absence of transverse filtration for various diffusion coefficients of the gas components: 1) $D = 0.1D_{air}$; 2) D_{air}; 3) $3D_{air}$; 4) $10D_{air}$. t, sec.

growth of perturbations of filtration combustion waves in the regime of low velocities (strong thermal coupling with the skeleton).

In the one-temperature approximation of the problem of filtration combustion of gases and in the absence of hydrodynamic factors, the absolute resistance of the front to small perturbations independent of the gas Lewis number has been shown.

Qualitative consideration has been given to the processes associated with the asymmetry of the diffusion and thermal transport in the filtration combustion front. In general, the investigation corroborates the conclusion that the FCG front is stable under these conditions.

The numerical calculations of the perturbation evolution performed with a wide (two orders of magnitude) variation of the gas Lewis number show that at the characteristic parameters of the system of filtration combustion in the practically realized mixtures the diffusion-thermal asymmetry cannot lead to the appearance or growth of small perturbations of the front. In so doing, the calculations demonstrate the possibility of the appearance of perturbations in the gas phase and their complex interaction with the temperature front in a porous medium. A detailed study of these interactions at various system parameters (particle size, composition of the combustible mixture, size of perturbations) can be the subject of further investigations.

The present investigation shows that the key to understanding the phenomenon of site instability under filtration combustion of poor hydrogen–air mixtures should be sought in the thermohydrodynamic factors.

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NOTATION

a, mass fraction of the limiting component; A, perturbation amplitude, m; b_1, b_2, b_3, coefficients, 1/m; c, specific heat capacity, J/(kg·K); D, diffusion coefficient, m^2/sec; D_{air}, diffusion coefficient of methane in air, m^2/sec; d, diameter, m; E, activation energy, J/mole; f, g, h, coefficients of the perturbation method; h_i, specific enthalpy of the limiting component, J/kg; H^+, rate of enthalpy increase due to diffusion, W; H^-, rate of heat outflow due to heat conduction, W; ΔH, total rate of enthalpy increase, W; k, perturbation wave number, 1/m; Le, Lewis number; m, flow rate of the limiting component in the combustion zone per unit area of the front, kg/(m^2·sec); n, normal; Q, thermal effect of reaction per unit mass of the limiting component, J/kg; R, universal gas constant, J/(mole·K); r, radius, m; S_D and S_λ, surface areas of mass and heat transfer, m^2; T, temperature, K; ΔT_{max}, difference between the temperature of the front and the temperature far before it, K; ΔT_{ad}, same for the adiabatic flame, K; t, time, sec; u, velocity, m/sec; $\bar{u}_w$, dimensionless combustion wave velocity; x and y, coordinates across and along the front, m; α_V, volume coefficient of interphase heat transfer, W/($m^3 \cdot K$); β, angle, rad; δ_D and δ_λ, concentration and thermal thicknesses of the front, m; ε, initial perturbation amplitude, m; κ, thermal diffusivity, W/(m·K); ρ, density, kg/m^3; Φ, stoichiometric ratio; ω, perturbation increment, 1/sec. Subscripts: 0, for a long distance before the front; (0), unperturbed solution; c, front curvature; d, dispersion; f, front; g, gas phase; con, convex part of the front; p, particle; s, solid phase; sp, specific value; th, thermal wave; w, wave; ~, effective value; ′, perturbation; air, air; ad, adiabatic, max, maximum.

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