FILTRATION COMBUSTION IN HYDROCARBON DESORPTION FROM A POROUS MEDIUM

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We have investigated theoretically and experimentally the process of filtration combustion with hydrocarbon desorption from a porous skeleton realized, in particular, in heat cleaning of porous media out of residues of organic impurities. The problem on the wave of such a combustion in a system with three phases — gaseous, liquid, and inert solid — has been solved analytically. The specific features of this process as compared to the traditional process of filtration combustion of gases have been revealed. The dependences of the basic characteristics of the waves on the content of methane in the gas mixture as well as of oil and water in a porous medium have been obtained. A comparison with the experimental data has been made. Recommendations for optimizing the operation of decontamination plants on the basis of the process considered are given.

Problems connected with industrial waste reclamation and recycling are becoming increasingly urgent. An important class of such problems is the decontamination of adsorbents and other porous media containing the phase of liquid hydrocarbons or other combustible substances bound on their surface, in particular, the problem of regeneration of zeolite sorbents from residues of transformer and machine oil. The conventional thermovacuum method [1] of recovery of the sorption properties of zeolite does not permit getting rid of solid-phase contaminants. Attempts to burn off organic impurities were unsuccessful because of the release into the atmosphere of large amounts of unoxidized organic matter. The regeneration of sorbents in the filtration combustion (FC) wave is a quite promising alternative method, since it makes it possible to fairly completely burn evaporated organic matter [2] and use the heat of its combustion to maintain the process, which considerably reduces expenditures of energy.

In principle, the technique of using the heat wave of filtration combustion to recycle porous substances is not novel and was developed to regenerate some types of catalyzers. However, fuel desorption produces a specific effect on the characteristics of the process of filtration combustion. The regimes realized in such a process require theoretical and experimental studies.

Filtration combustion with evaporation of additional fuel from the condensed phase is a little-studied process [3] which has good prospects for industrial use. Works in this field are mainly focused on the investigation of the combustion of aerosols [4–6] and liquid, in particular, monofuel [7, 8]. For instance, in [7] the FC of a monofuel — hydrazine — was investigated and dynamic characteristics of the combustion wave were obtained. The possibilities of controlling the process that appear in using low-calorific-power combustible mixtures in filtration combustion systems with a liquid phase have up to now been little studied.

In the present paper, theoretical and experimental studies of the filtration combustion of gases in hydrocarbon desorption from a porous medium have been made. The basic features of the thermal regime and dynamics of FC waves have been revealed. The influence of water additives on the heat-wave characteristics has been analyzed. Recommendations on the realization of the practically important process — removal of organic contaminants from a zeolite sorbent — have been given.

Experimental. The experimental studies of the FC with desorption of organic matter from a porous medium were performed on a gas stand schematically represented in Fig. 1. As a reactor, a quartz cylinder of diameter 0.07 m and height 0.4 m was used. The reactor fill was formed from three alternating layers: Al_2O_3 balls (where the combustion wave was initiated and formed) — zeolite — Al_2O_3 balls. The fill porosity was $\varepsilon \cong 0.4$. Combustion was initiated
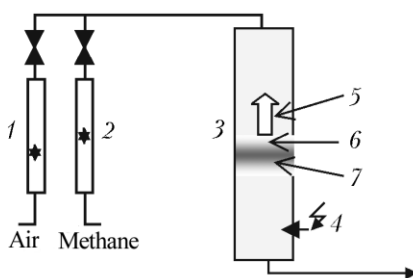

Fig. 1. Scheme of the zeolite cleaner in the counter-running FC wave regime: 1, 2) rotamers with regulating valves; 3) reactor; 4) spark ignition; 5) direction of combustion-front movement; 6) oil evaporation front; 7) combustion zone.

TABLE 1. Experimental Data (for an air flow rate of 1000 liters/h)

Experiment number	Methane flow rate, liters/h	Φ	u_w, m/sec	$T_{s,m}$, K
1	75	0.73	$-2.8 \cdot 10^{-5}$	1300
2	50	0.45	$-3.3 \cdot 10^{-5}$	1380
3	23	0.18	$-5.0 \cdot 10^{-5}$	1400
4	80	0.75	$-2.8 \cdot 10^{-5}$	1220

by a spark device in the Al_2O_3 balls with a stoichiometric composition of the combustible mixture. A quartz capillary, into which a movable thermocouple was introduced, was placed inside the cylinder.

In the case of a cocurrent combustion wave, organic vapors freely go out into the atmosphere, which requires inclusion in the system of an additional device for cleaning waste gas and thus complicates the plant and increases the process cost. In the counterrunning combustion wave, oil vapors formed before the front (Fig. 1) pass through the reaction zone of the wave and burn as an additional fuel.

The combustion-front velocity was determined visually by means of a ruler and a timing device. The experimental results are given in Table 1. The mass fractions of oil and water (of the filling mass of zeolite) were estimated, respectively, as $\chi \cong 0.1$ and $\psi \cong 0.054$. In experiment 3, despite the much smaller discharge of methane than in the other series of measurements, the wave-front velocity and, consequently, the capacity of the cleaning process is much higher. Note that in experiments 1, 2, and 4 the wave velocity was not constant. First the combustion front reached the nonannealed layer of zeolite and began to die out and slow down, and the wave-front temperature thereby remained fairly high (≥ 1100 K). But when the layer was annealed, the wave front flared up again and its propagation velocity increased. When the wave reached the nonannealed zeolite layer, the cycle was repeated.

The experiments have shown that annealing does not affect zeolite granules and this cleaning process is ecologically relatively clean. Since gaseous combustion products completely oxidize, to provide a possibly lower temperature in the wave front (to save zeolite from destruction and corrosion), it is expedient to wet the porous medium with water. Optimization of the system parameters can make the process relatively cheap. This method can also be used to clean other sorbents (catalyzers) out of organic contaminants.

To elucidate the temperature and dynamic features of this kind of FC and choose an optimum regime of the process, a theoretical study has been made.

Mathematical Model. The equations describing the FC wave propagation in a porous medium with a liquid phase can be written in the following form:

$$\rho_g \frac{\partial T_g}{\partial t} + c_{pg} G \frac{\partial T_g}{\partial x} = \varepsilon \rho_g H_1 K Y_1 \exp\left(-E/(RT_g)\right) + \frac{\partial}{\partial t} Q_2 + \frac{\partial}{\partial t} Q_3 + \alpha_v (T_s - T_g), \tag{1}$$

$$(1-\varepsilon) c_s \rho_s \frac{\partial T_s}{\partial t} = (1-\varepsilon) \frac{\partial}{\partial x} \lambda_s \frac{\partial T_s}{\partial x} - \alpha_v (T_s - T_g), \tag{2}$$

$$G\frac{\partial Y_i}{\partial x} = \varepsilon\rho_g K Y_i \exp\left(-E/(RT_g)\right), \quad i = 1, 2. \tag{3}$$

The mixture enters the system with a constant mass flow $G = \varepsilon\rho_g u_g$. Here we use the equations for filtration combustion of gases (FCG) from [3, 9, 10] to which we added source terms of the form $\partial Q_k/\partial t$, $k = 2, 3$, that are due to the presence of the liquid phase and correspond to the heat released in oil vapor combustion (Q_2) or the heat absorbed in water evaporation (Q_3). Since the chief aim of this model is to determine the summed energy balance in the wave, the additional sources are assigned to the gas phase.

We assume that with the approach of the wave combustion front all the liquid contained in the porous medium is evaporated and combustion proceeds in the gas-phase reactions. Such a simplified representation of the process, in particular, excludes the possibility of the proceeding of cycles: evaporation → condensation → evaporation, and so on. It is also assumed that the water present in the porous medium always evaporates completely and does not participate in the reactions (is chemically inert).

Similarly to [3, 9, 10], in Eqs. (1)–(3) the transition to a coordinate system moving together with the wave front at a constant velocity u_w has been made, and using the boundary conditions

$$T_s\big|_{-\infty} = T_g\big|_{-\infty} = T_0, \quad \partial T_s/\partial x\big|_{\pm\infty} = \partial T_g/\partial x\big|_{\pm\infty} = 0;$$

$$T_g\big|_{-0} = T_{g,i}, \quad T_g\big|_{+0} - T_g\big|_{-0} = \Delta\widetilde{T}_a;$$

$$T_s\big|_{-0} = T_s\big|_{+0}, \quad \partial T_s/\partial x\big|_{-0} = \partial T_s/\partial x\big|_{+0} \tag{4}$$

and integrating (1)–(3) with respect to x from $-\infty$ to $+\infty$, we can obtain the FC wave balance equation:

$$T_{s,m} = T_{en} + \frac{\Delta T_{1a} + |u|\,\Delta T_{2a}}{1 - u}. \tag{5}$$

Here $\Delta T_{1a} = H_1/c_{pg}$ and $|u|\Delta T_{2a}$ is the adiabatic heat build-up of the methane-air mixture and oil vapors, respectively; $u = u_w/u_{th}$ is the dimensionless velocity of wave-front propagation, and $u_{th} = c_{pg}/G[(1-\varepsilon)c_s\rho_s]$ is the heat-wave velocity.

It should be emphasized that the balance equation (5) includes the resulting adiabatic heat built-up of the system $\Delta\widetilde{T}_2(u) = \Delta T_{1a} + |u|\Delta T_{2a}$, which, unlike the FCG wave [9], is an explicit function of the front velocity, the liquid-phase combustion heat, and other parameters of the porous medium.

An important element of the model is the account of the oxygen consumption in the system. Depending on the presence of an oxidizer, complete burn-out (CB) and incomplete burn-out (IB) of organic matter is possible. In the latter case, unwanted release of hydrocarbons from the system into the atmosphere is possible.

Introducing the mass flow of oil vapor G_2

$$G_2 \equiv |u_w|\,\rho_s\,(1-\varepsilon)\,\chi = \frac{|u|\,c_{pg} G\chi}{c_s}, \tag{6}$$

we give the condition of oxygen deficiency for oxidation of oil entering the wave front with the rate of flow G_2 in the form

$$\frac{G_2}{C_2}\left(\frac{F}{A}\right)_{2st}^{-1} > \frac{G\,(1-\Phi)}{v_n\rho_{g,en}}. \tag{7}$$

Here $(F/A)_{st}$ is the stoichiometric relations, Φ is the equivalent relation for the methane-air mixture, C_2 is the molar mass of condensed organic matter, and v_n is the molar volume of gas under normal conditions.

Inequality (7) can be rewritten as the condition of excess over some critical flow of oil vapor G_2^*:

$$G_2 > G_2^*, \quad G_2^* = \frac{GC_2(1-\Phi)}{v_n\rho_{g,en}}\left(\frac{F}{A}\right)_{2st}. \tag{8}$$

Relation (8) defines the boundary between the CB and IB regimes for the FC wave. For practical estimations, it is convenient to represent the critical condition (8) in the equivalent form

$$|u_w| > |u_w^*|, \quad |u_w^*| = \frac{GC_2(1-\Phi)}{v_n\rho_{g,en}\rho_s(1-\varepsilon)\chi}\left(\frac{F}{A}\right)_{2st} \tag{9}$$

or

$$|u| > |u^*|, \quad |u^*| = \frac{c_sC_2(1-\Phi)}{v_n\rho_{g,en}c_{pg}\chi}\left(\frac{F}{A}\right)_{2st}. \tag{10}$$

Let us introduce the degree of burn-out of condensed organic matter χ':

$$\chi' \equiv \frac{G_2^*}{|u_w|\rho_s(1-\varepsilon)\chi}. \tag{11}$$

Thus, to the CB regime there corresponds $\chi' = 1$, and in the case of incomplete burn-out $\chi' < 1$. Accordingly, the total heat build-up $\Delta\tilde{T}_a$ will be determined as

$$\Delta\tilde{T}_a(u) \cong \Delta T_{1a} + \frac{|u|}{c_s}(\chi H_2 - \psi H_3) \tag{12}$$

in the CB regime ($G_2 \leq G_2^*$) and

$$\Delta\tilde{T}_a(u) \cong \Delta T_{1a} + \frac{C_2H_2(1-\Phi)}{v_n\rho_{g,en}c_{pg}}\left(\frac{F}{A}\right)_{2st} - |u|\frac{\psi H_3}{c_s} \tag{13}$$

in the IB regime ($G_2 > G_2^*$).

From the point of view of this model and the above assumption for certain characteristics of the FC wave one can use the known solutions for filtration combustion waves of gases. In particular, we shall use the analytical expression from [11] obtained in the approximation of a narrow reaction zone:

$$T_{s,m} \cong \frac{\Delta\tilde{T}_a}{1+a} + \frac{E}{R \ln\dfrac{\varepsilon c_{pg}\rho_{g,en}T_{en}K(1+a)}{\alpha_v\Delta\tilde{T}_a}}, \tag{14}$$

where $a = (1-\varepsilon)\lambda_s\alpha_v/(c_{pg}G)^2$ is the dimensionless parameter.

Results and Discussion. To calculate the maximum temperature and velocity of the FC wave front, the system of equations (5), (12)–(14) was solved for the following values of parameters: $\varepsilon = 0.49$, $c_s = 794$ J/(kg·K), $\rho_s = 3.15\cdot10^3$ kg/m^3, $c_{pg} = 1.3\cdot10^3$ K/(kg·K), $\lambda_{s,en} = 1.0$ W/(m·K), $d = 6$ mm, $(F/A)_{1st} = 0.11$, $E = 1.3\cdot10^5$ J/(mole·K), and $K = 2.6\cdot10^8$ sec^{-1} [12]. The heat conductivity and interphase heat-transfer coefficients were determined in accordance with [10, 13]

$$\lambda_s = \lambda_{s,en} + \frac{32\varepsilon\sigma d}{9(1-\varepsilon)}T_s^3, \tag{15}$$

TABLE 2. Value of the Adiabatic Heat Build-up of the Methane-Air Mixture Depending on the Equivalent Relation

Φ	0.05	0.18	0.42	0.45	0.73
ΔT_{1a}, K	142	485	1023	1083	1594

$$\alpha_v = \frac{\pi \lambda_g}{d^2} (2 + 1.1\, Re^{0.6}\, Pr^{1/3}) . \tag{16}$$

The data for ΔT_{1a} used in the calculations are given in Table 2. It is considered that machine oil (in the liquid phase) consists of light fractions and is mainly represented by tetradecane ($C_{14}H_{30}$), for which the brutto-reaction of complete oxidation is of the form

$$C_{14}H_{30} + 21.5O_2 + 80.84N_2 \rightarrow 15H_2O + 14CO_2 + 80.84N_2 . \tag{17}$$
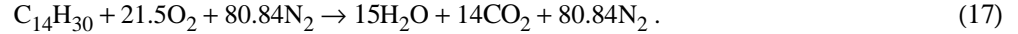
It is also assumed that the global kinetic combustion coefficients of oil vapor are close to the respective data of the methane-air mixture and in the first approximation they can be considered to be equal. To model the tetradecane oxidation, we used the following values of the parameters: $(F/A)_{2st} = 0.1\cdot 10^{-2}$; $H_2 = 5.1\cdot 10^7$ J/kg; $C_2 = 198\cdot 10^{-3}$ kg/mole. The water evaporation heat (taking into account the heating from ambient temperature to 100°C) was estimated as $H_3 \cong 2.55\cdot 10^6$ J/kg. The heat of oil desorption from zeolite H_{2des} was neglected ($H_{2des} << H_2$), since according to the estimates of [14] $H_{2des}/H_2 \cong 0.024$.

Let us analyze the influence of the most important parameters of the process — methane, oil, and water concentrations — on the FC wave characteristics. Figure 2 shows the calculated dependences of the wave-front velocity u_w, the maximum temperature of the skeleton $T_{s,m}$, and the degree of burn-out χ' on the gas flow for various concentrations of methane and oil.

Consider the behavior of the system with decreasing gas flow beginning with the moment the wave goes from the cocurrent regime of propagation to the counterpropagation one. From Fig. 2 it is seen that as oil vapor enters the reaction zone, the front velocity and the maximum temperature of the skeleton sharply increase, which shows up as a "kink" on the $u_w(G)$ curve distorting the U-shaped front-velocity-flow curve characteristic of FCG waves [3]. Such "kinks" and their respective nonmonotonic regions (i.e., regions where the maximum temperature of the skeleton decreases with increasing flow) of the $T_{s,m}(G)$ dependence are distinguishing attributes of the filtration waves with evaporation and combustion of the liquid phase (compared to the FCG waves).

In the system under investigation, considerably larger values of $|u_w|$ and $T_{s,m}$ compared to the FCG waves with the same concentration of methane in the mixture (see, e.g., the family of curves for $\Phi = 0.73$ in Fig. 2) are attained. The above properties of the system explain the experimentally observed effects of extinction and deceleration of the wave front upon the warming-up of the next layer of zeolite (since oil and water evaporation requires additional expenditures of energy), as well as of "acceleration" and "burning-up" of the front as oil vapor enters the reaction zone.

Complete oxidation of complex organic matter requires large consumptions of oxygen ($\approx$20 moles per tetradecane mole); therefore, the critical condition (7)–(10) for the beginning of the IB regime is reached fairly fast. As a result, the degree of burn-out χ' has a maximum and rapidly decreases with decreasing gas flow (see Fig. 2). As a consequence of this, the regime of complete burn-out takes place only in a rather narrow range of parameters. The value of the gas flow corresponding to the change-over from the CB to the IB regime strongly depends on the methane concentration and shifts towards smaller values with decreasing Φ.

In practice, even in the regime of considerably "incomplete" burn-out there will be no marked releases of non-oxidized organic matter from the system, since the gas phase will pass through the wave-annealed region of zeolite with recovered sorption properties and will be reabsorbed with a high probability. From the ecological point of view, such a "safety factor" of the process under consideration is an additional advantage of this cleaning technology.

It is interesting to note that in the IB regime (on the side of "small" expenditures) the shape of the u_w, $T_{s,m}(G)$ curves is similar to the analogous curves for the filtration combustion of gases, which is due to the fulfillment of the condition $\Delta \tilde{T}_a(u) \cong$ const. In this case, an increase in the mass content of oil χ in a porous medium does not
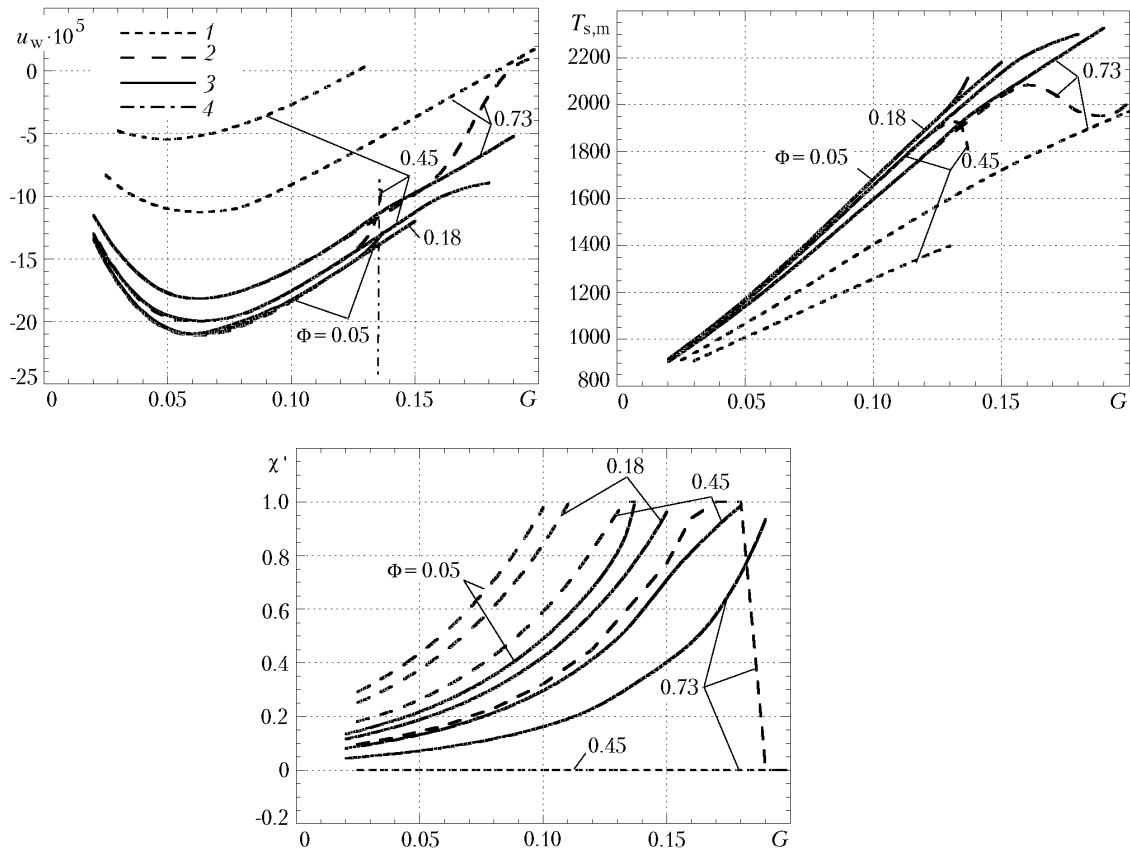
Fig. 2. Wave-front velocity u_w, skeleton maximum temperature $T_{s,m}$, and degree of burn-out χ' as a function of the gas flow rate for various concentrations of methane and the mass fraction of oil: 1) $\chi = 0$; 2) 0.05; 3) 0.1; 4) transition point of CB to IB for $\Phi = 0$. u_w, m/sec; $T_{s,m}$, K; G, kg/(m$^2 \cdot$sec).

affect the wave characteristics (see Fig. 2). But the portion of the sharp "kink" of the $u_w(G)$ curve is due to the greatly varying function of the overall adiabatic heating of the system ($\Delta \tilde{T}_a(u) \neq$ const).

The features of the behavior of the FC waves in the regime of complete burn-out can be considered in more detail by "extending" the CB existence zone to a wider region of expenditures, which is achieved by decreasing the oil content χ in the system and/or increasing the methane concentration (see Fig. 3). It is seen from Fig. 3 that a specific feature of the $T_{s,m}(G)$ curve (distinguishing this type of filtration combustion from FCG) is the nonmonotony of the $T_{s,m}(G)$ curve which shows up as the fact that the skeleton temperature may increase with decreasing gas flow. It is important to note the nontrivial fact that this portion of the growth of the $T_{s,m}(G)$ dependence coincides with the portion of the "kink" of the $u_w(G)$ curve and corresponds to the region of the CB regime, which can be used in practice to choose optimum (in terms of purity of sorbent cleaning) operating conditions of the system. Taking into account that on the limit of the appearance of such a nonmonotony the function $T_{s,m}(G) \cong$ const (see, e.g., the data for $\Phi = 0.45$, Fig. 3) and varying (5), we obtain the following condition needed for the maximum in the $T_{s,m}(G)$ to exist:

$$\Delta T_{1a} < \Delta T_{2a} \equiv \frac{\chi H_2 - \psi H_3}{c_s}, \tag{18}$$

which, in particular, is attained in the case of fairly low-calorific-value (low Φ values) methane-air mixtures.

Note one more feature of the system in the CB regime, which is unusual for the filtration combustion of gases: a practically linear dependence of the wave-front velocity on the gas flow rate (see Fig. 3). Indeed, from the condition $T_{s,m}(G) \cong$ const, in view of balance (5), one can obtain the expression
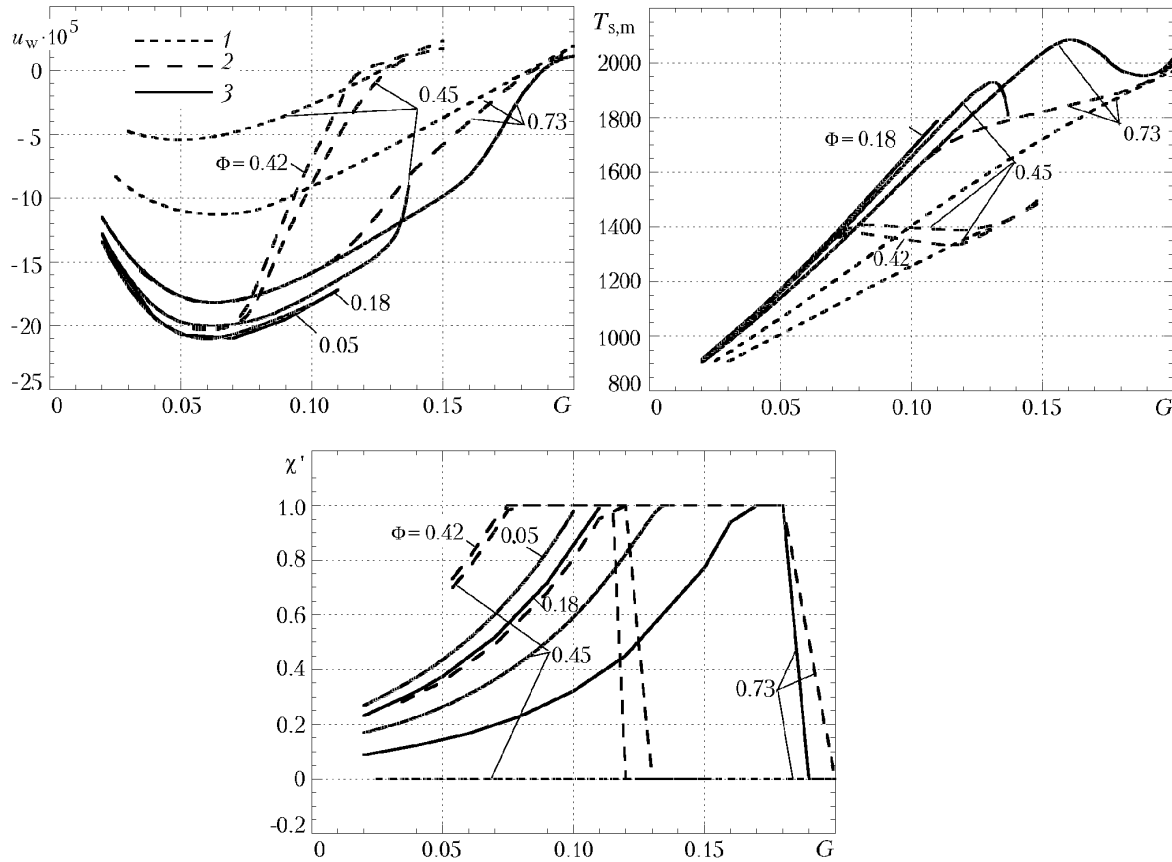
Fig. 3. Wave-front velocity u_w, skeleton maximum temperature $T_{s,m}$, and degree of burn-out χ' versus the gas flow rate for small values of the mass fraction of oil: 1) $\chi = 0$; 2) 0.02; 3) 0.05. u_w, m/sec; $T_{s,m}$, K; G, kg/(m^2·sec).

$$u_w \cong \frac{\Delta T_{s,m} - \Delta T_{1a}}{\Delta T_{2a} - \Delta T_{s,m}} u_{th} \sim G . \qquad (19)$$

From the form of function (19) the conclusion also follows that with decreasing methane concentration the tilt of the "kink" in the $u_w(G)$ dependence increases:

$$\partial u_w / \partial \Delta T_{1a} \cong - u_{th} / (\Delta T_{2a} - \Delta T_{s,m}) , \qquad (20)$$

which also agrees with the calculated dependences (see Fig. 3).

In the limit of small concentrations of methane ($\Phi \to 0$), where $\Delta T_{1a} \ll \Delta T_{2a}$, the tilt of the "kink" tends to $\pi/2$, and the region of the CB regime shrinks up to a point ($\Phi < 0.18$, Fig. 2). And vice versa, when the calorific values of the methane-air mixture and oil vapor become equal ($\Delta T_{1a} \sim \Delta T_{2a}$), the "kink" in the $u_w(G)$ dependence becomes "gently sloping" and the region of expenditures corresponding to the regime of complete burn-out expands and becomes comparable in size to the region of incomplete burn-out ($\Phi = 0.73$, Fig. 2).

A practically important method for controlling this process is the addition of water to the porous medium. This makes it possible to lower the temperature in the wave reaction zone and, consequently, preserve the zeolite. The calculated dependence of the wave characteristics on the mass content of water in a porous medium is shown in Fig. 4.

From the data given in Fig. 4 it is seen that the addition of water leads to a decrease in $T_{s,m}$ by 70–150 K and a considerable decrease in the front velocity depending on the flow rate and concentration of methane, which is explained by the reduction of the heat release in the system as a result of the heat expenditures in water evaporation. In this case, an interesting feature of the process is also a marked increase in the completeness of oil burn-out, which increases the capacity of the sorbent cleaning process (see Fig. 4).
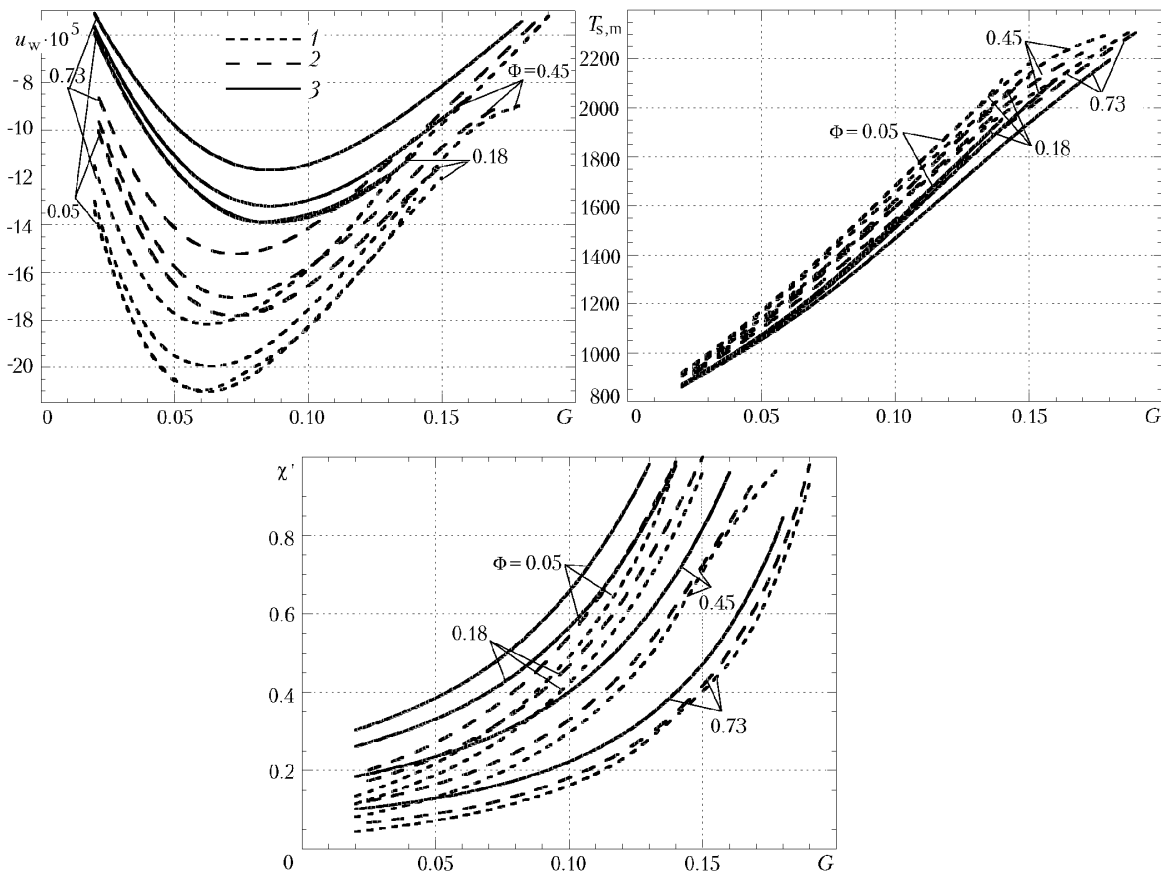
Fig. 4. Wave-front velocity u_w, skeleton maximum temperature $T_{s,m}$, and degree of burn-out χ' versus the gas flow rate for various concentrations of methane and water content ($\chi = 0.1$): 1) $\psi = 0$; 2) 0.1; 3) 0.3. u_w, m/sec; $T_{s,m}$, K; G, kg/(m^2·sec).

In the general case, the choice of parameters of the process of thermal regeneration of zeolite is directed towards optimizing the following basic factors: increase in χ' and u_w (this factor increases the capacity of the cleaning process), decrease in $T_{s,m}$ (preserves zeolite) and Φ (decreases the cost of the process), expansion of the region of existence of the CB regime (which facilitates the realization of high degrees of cleaning in the case of fluctuation of the outer parameters of the system).

From the data given in Figs. 2–4 it is seen that the typical choices are: "rate" or "purity" of cleaning of the porous medium; "CB region width" or "cleaning rate," etc. For example, a decrease in the concentration of methane is energetically advantageous and increases the cleaning rate of zeolite, but at the same time it sharply narrows the region of the CB regime, which makes it difficult to provide stability of the process characteristics. In general, the addition of water is very desirable, since this decreases the skeleton temperature, increases the degree of burn-out, and widens the region of the CB regime, but at the same time it noticeably decreases the cleaning rate. The latter lowers the total capacity of the process. Therefore, the optimum choice of the system parameters should be based on concrete technological limitations of the process and the sorbent properties.

In conclusion, note that an important parameter of the proposed system is the relation between the heat content of the methane-air mixture and the adsorbed organic vapor. Figure 5 shows how the shape of the calculated $T_{s,m}$ and $u_w(\Phi)$ curves change depending on the oil combustion heat H_2. The same figure also gives the experimental data from Table 1. It is seen that the experimentally observed monotonic decrease in $T_{s,m}$ and u_w is only achieved at fairly high values of $H_2 \geq 5.1 \cdot 10^7$ J/kg, which is explained by the respective decrease in the total adiabatic heating $\Delta \tilde{T}_a$ with increasing Φ in this case. These considerations have determined the choice of the value of $H_2 = 5.1 \cdot 10^7$ J/kg for parametric calculations.
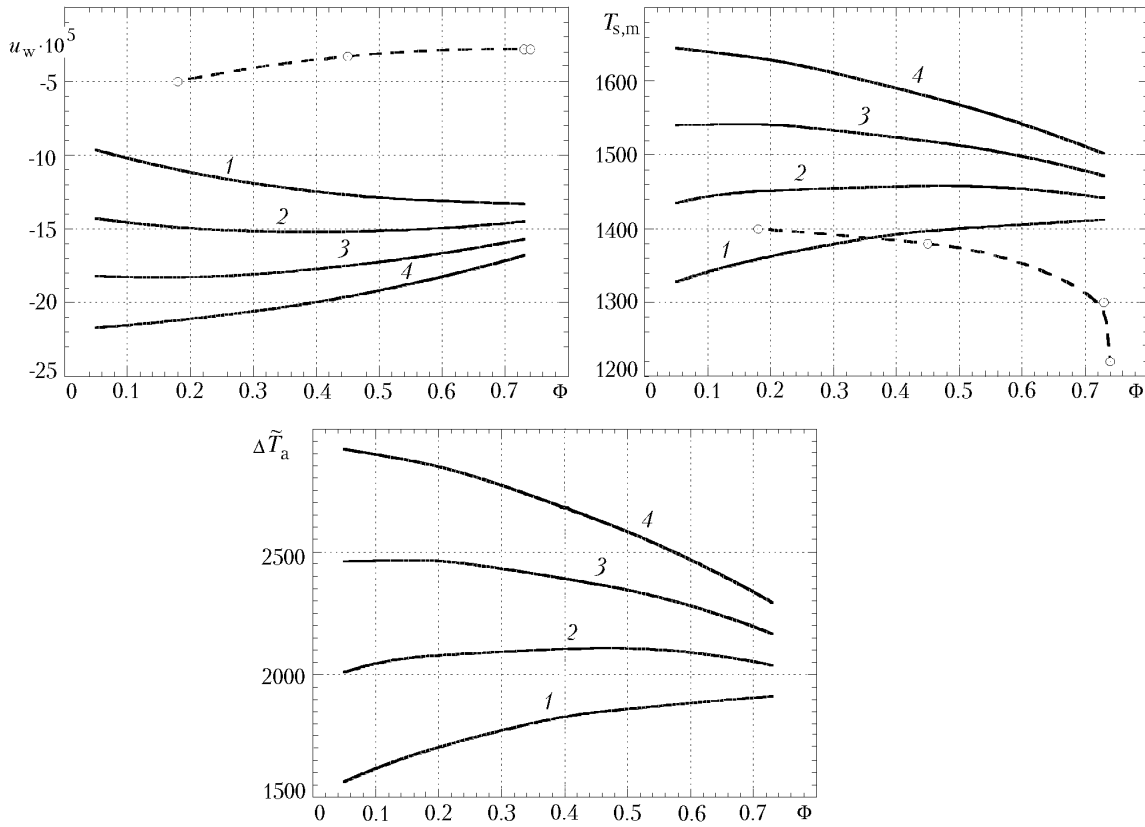
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Fig. 5. Wave-front velocity u_w, skeleton maximum temperature $T_{s,m}$, and temperature of resulting adiabatic heating up $\Delta \widetilde{T}_a$ versus the methane content for various values of the combustion heat of adsorbed organic matter: 1) $H_2 = 31$ MJ/kg; 2) 41; 3) 51; 4) 61; $\chi = 0.1$; $\psi = 0.054$; $G = 0.1$ kg/(m^2·sec); dots, experiment (according to Table 1). u_w, m/sec; $T_{s,m}$, $\Delta \widetilde{T}_a$, K.

Thus, in the present paper, the possibility of realizing a controlled process of oxidation of organic matter adsorbed in a porous medium in the filtration combustion wave has been substantiated. The relation between the temperature and dynamic parameters of the wave and other characteristics of the system, in particular, the amount of adsorbed organic matter and the air and fuel gas (in the case under consideration — methane) flow rate has been shown. The proposed model permits optimizing practical systems of cleaning porous and free-flowing media. The results of the investigation have a fairly wide field of application and can be used for qualitative description of the properties of three-phase systems with a different state of the organic matter in a porous medium (in the liquid or solid phase) — in the form of a binding component of composite materials, gasifying solid-fuel additives, etc.

NOTATION

c, specific heat, J/(kg·K); d, fill grain diameter, m; E, activation energy, J/(mole); H, combustion heat, J/kg; G, mass flow rate, kg/(m^2·sec); K, pre-exponential factors, sec^{-1}; Pr, Prandtl number; Q, heat release, W/m^3; R, universal content, J/(mole·K); Re, Reynolds number; t, time coordinate, sec; T, temperature, K; u_w, wave-front velocity, m/sec; u_g, speed of filtration, m/sec; x, space coordinate, m; Y, dimensional concentration of fuel; σ, Stefan–Boltzmann constant, W/(m^2·K^{-4}); α_v, interphase heat-transfer coefficient, W/(m^3·K); ρ, density, kg/m^3; ε, porosity; Φ, equivalent relation for the methane-air mixture; λ_s, heat-conductivity coefficient, W/(m·K); χ and ψ, mass fractions of organic matter and water; χ', degree of burn-out. Subscripts: a, adiabatic; d, desorption; n, normal conditions; p, pressure; v, volume; g, gas; s, skeleton; en, environment; m, maximum; th, thermal; st, stoichiometric; w, wave; 1, methane; 2, oil; 3, water.

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