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Water purification of organic inclusions by the method of combustion within an inert porous media

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ABSTRACT

New technology of water purification of organic inclusions or solutes by using a filtration combustion recuperative reactor ("tube-in-tube" type) is investigated numerically. An acetone aqueous solution served as a model liquid. The model was verified on the basis of experimental temperature measurement data.

The physical reason for the comparatively high energy consumption at the startup of the reactor has been revealed. The minimum concentration limit (MCL) for self-sustained operation as a function of the reactor length, size of a packed bed particle, and of the heat transfer coefficients was investigated. Thermal insulation has the strongest effect on MCL, which may be as low as $c = 0.12$ for the acetone aqueous solution and characteristic length of the reactor $L = 0.5$ m. Increase of the length of the reactor has a limited potential for reduction of the MCL. This is connected with the exponential saturation of the recuperated heat and simultaneous increase in the heat loss with the length of the reactor. In the case of proportional elongation of reactor, when the "dead end" area grows, not a decrease but an increase in the MCL value is observed.

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1. Introduction

Water purification of organic inclusions stands now as an important and complex challenge for various industries. The problem is urgent because of the general deterioration of the ecological situation in the world.

Organic inclusions may be present in water in the form of relatively stable emulsions (for example, lubricants–coolants) as well as in the form of solutions. Sorption and distillation are used for water recovery from solutions. However, the latter can be ineffective if the boiling points of water and solute are close. Emulsion destruction can be done by thermal, biochemical, electrochemical, and other methods [1–3], all of which are power consuming or demand utilization of toxic chemicals. Furthermore, new products may appear in the process of destruction which would require additional treatment/utilization. Taking into consideration the above-mentioned development of new methods, water recovery should be considered as an important task.

Among the promising methods of oxidation purification of gases and solids there is the method of filtration combustion or excess enthalpy combustion. The idea of the use of filtration combustion for water purification was firstly proposed in [4] and tested in [5]. Development of this investigation with the aim of the process

optimization and minimization of power consumption is particularly urgent problem.

Filtration combustion (FC) (or combustion within inert porous media) is a relatively new area of the combustion science which attracted the attention of specialists in the recent decade mainly due to the extraordinary potential of combustion of extra-lean and extra-rich fuel mixtures [6–8]. An increase in the local enthalpy characteristic for the FC system is produced due to the interphase heat exchange within the transient thermal wave or at reverse flow heat recirculation ("tube-in-tube" reactor). The advantage of the latter type of reactor is a steady-state operation. The drawback is the scaling limitations [9].

The principal possibility of combustion of a water–organic solution or a mixture in the FC reactor was shown in [5]. An acetone–water mixture was burned in the "tube-in-tube" type reactor. The temperature field was stabilized with the help of electric heaters that served also for ignition. High quality purification of water was demonstrated. Analysis of the energy balance as a function of the mass flow rate and acetone concentration was performed. The problem of the process optimization, as well as of the influence of geometrical and other factors on the process was not touched in [5]. Regular parametric investigations of this system are necessary to create a basis for its use in practice. In particular, it is important to determine the minimal concentration of the organic component that provides self-sustained oxidation without electric heating. The characteristic features of the temperature field, reactor startup,

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Nomenclature

c	concentration of acetone in liquid	T_0	initial temperature of the system (K)
c_w	mass concentration of liquid (kg/m ³)	\mathbf{u}	filtration velocity vector (m/s)
\mathbf{D}	gas diffusivity tensor	Y_i	mass fraction of the i th gas chemical component
\mathbf{D}_d	dispersion diffusivity tensor	z	longitudinal coordinate (m)
D_p	longitudinal component of dispersion diffusivity		
D_t	transverse component of dispersion diffusivity	<i>Greek</i>	
D_g	diffusivity coefficient (cm ² /s)	α_{vol}	volumetric interphase heat transfer coefficient (W/K/m ³)
d_0	packed bed particle diameter (m)	α	coefficient of heat exchange with the ambient (W/K/m ²)
d_1	diameter of the internal tube (m)	ε	emissivity of the embedded particles
d_2	diameter of the external tube (m)	λ	conductivity (W/m/K)
G	specific flow rate (kg/(m ² s))	μ	gas viscosity (Pa s)
h_i	mass enthalpy of i th chemical component (J/kg)	Λ	heat conductivity tensor $\Lambda = c_p \rho_g \mathbf{D}$
\mathbf{I}	unit matrix	ρ	density (kg/m ³)
I_{ev}	evaporation rate (kg/(m ³ s))	$\dot{\rho}_i$	mass generation of i th component due to chemical reactions
k_0, k_1	filtration permeabilities	σ	Stefan–Boltzmann constant
L	burner length (m)	τ_z, τ_r	axial and radial components of the velocity vector projection
l	length of the internal tube (m)		
M	average molecular weight of gas (kg/mol)	<i>Subscripts</i>	
M_w	molar mass of liquid (kg/mol)	1	internal tube
m	porosity	2	external tube
Pr	Prandtl number	g	gas
P	power of a heater (W)	i	i th component of a gas
p	pressure (Pa)	s	solid
p_0	outlet pressure (Pa)	liq	liquid
p_{sat}	saturated vapor pressure (Pa)		
R	gas constant		
r	radial coordinate (m)		
T	temperature (K)		

and of the system operation should be investigated. The task of optimization of the reactor length, diameter, and insulation width is important too.

In this work, we present the results of systematic numerical investigations of the process of oxidational purification of water from dissolved organic components by using filtration combustion. The “tube-in-tube” type of a reactor was examined, the characteristic features of the process were explored numerically. The numerical model and computational algorithm have been validated by comparing with experimental data. The minimum concentration limit (MCL) for self-sustained operation of the system and the MCL correlation with the length of the reactor are determined. The characteristic feature of the ignition of this system is discussed. Recommendations on the geometrical parameters of the reactor are given.

2. Statement of the physical problem

We consider a recuperative reactor of the “tube-in-tube” type, Fig. 1. The reactor is filled with an inert porous medium consisting of ceramic balls, and is thermally insulated from outside. The electric heating elements are placed at the bottom of the external tube. The air flow through the reactor (as depicted in Fig. 1) was provided by a suction fan. Electric heaters are used to startup the reactor. After the heating of the porous medium to a temperature of self-ignition of organic components, the electric heater is switched off and polluted water is fed into the central tube. On evaporation of water, the organic components of the combustible mixture pass through the hot zone, are burned out, and then pass through the external tube to a venting system. Normally, the reactor operates in a steady-state regime. If the heat content of the organic components is insufficient to sustain combustion, electric heaters may be

switched on. As a model combustible mixture we used a water-acetone mixture.

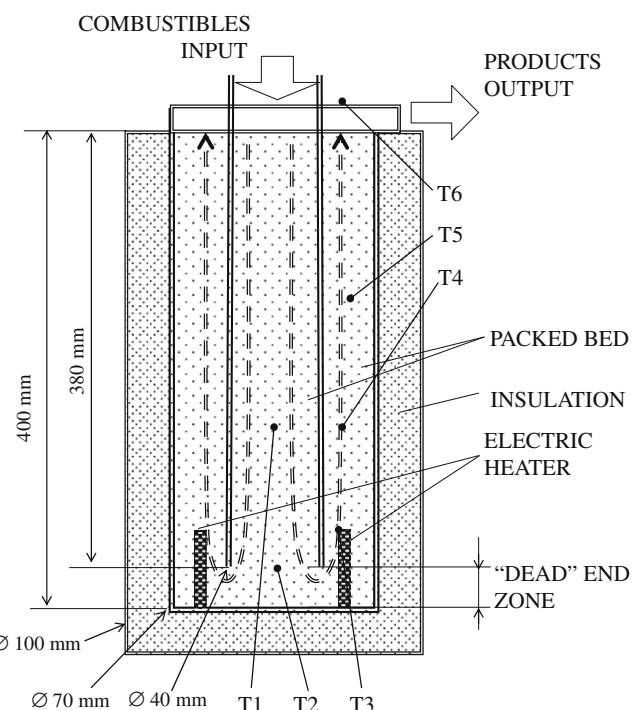


Fig. 1. Scheme of the “tube-in-tube” filtration combustion reactor. Geometrical dimensions, position of thermocouples (T1–T6) and heaters are depicted for experimental reactor [5].

The aim of the present investigation is to estimate a maximum temperature and the position of the combustion zone depending on the flow rate and concentration of organic components, the minimum concentration of organic components that provide self-sustained combustion, as well as other correlations between the parameters of the system.

3. Model formulation

A generalized volume-averaged model [10,11] was used to model the system. The set of equations included: continuity and pressure equations for a gaseous phase, conservation equations for gaseous components, energy conservation equations for a gas and solid, and the ideal gas state equation:

$$\frac{\partial \rho_g}{\partial t} + \nabla(\rho_g \mathbf{u}) = I_{ev}, \quad (1)$$

$$-\nabla p = \frac{\mu}{k_0} \mathbf{u} + \frac{\rho_g}{k_1} |\mathbf{u}| \mathbf{u}, \quad (2)$$

$$\rho_g \frac{\partial Y_i}{\partial t} + \rho_g \mathbf{u} \nabla Y_i - \nabla(\rho_g \mathbf{D} \nabla Y_i) = \dot{\rho}_i, \quad (3)$$

$$\rho_g c_p \frac{\partial T_g}{\partial t} + c_p \rho_g \mathbf{u} \nabla T_g - \nabla(\Lambda \nabla T_g) = \frac{\alpha_{vol}}{m} (T_s - T_g) - \sum_i h_i \dot{\rho}_i, \quad (4)$$

$$(1-m) \rho_s c_s \frac{\partial T_s}{\partial t} - \nabla(\lambda \nabla T_s) = \alpha_{vol} (T_g - T_s), \quad (5)$$

$$\rho_g = \frac{pM}{RT_g}. \quad (6)$$

The governing equations were supplemented with the conservation equation for the mass of the liquid injected into the system:

$$\frac{\partial c_w}{\partial t} + u_w \frac{\partial c_w}{\partial z} = -I_{ev}, \quad (7)$$

where u_w is the constant mean velocity of the liquid, equal to the ratio of the specific flow rate to the liquid concentration in the solid phase. The concentration is fixed at the inlet:

$$c_w|_{z=0} = c_{w,0} = \frac{4g_w}{\pi d_1^2 u_w}. \quad (8)$$

The system of Eqs. (1)–(7) is supplemented with the boundary conditions for temperature, concentration, and velocity. The gas flow rate and composition at the inlet are fixed. A constant pressure at the outlet is assigned. The Newtonian heat exchange with the ambient is used:

$$-\lambda \frac{\partial T_s}{\partial x} \Big|_{x=0.5d_2} = \beta (T_s|_{x=0.5d_2} - T_0). \quad (9)$$

Another condition used is the adiabatic condition.

The dispersion heat conductivity and diffusion of a gas were taken into account in calculations [12]. The diffusivity was calculated by the formula $\mathbf{D} = D_g \mathbf{I} + \mathbf{D}_d$, where $\mathbf{D}_d = \begin{bmatrix} D_p \tau_z^2 + D_t \tau_r^2 & (D_p - D_t) \tau_z \tau_r \\ (D_p - D_t) \tau_z \tau_r & D_p \tau_r^2 + D_t \tau_z^2 \end{bmatrix}$, $\tau = \frac{\mathbf{u}}{|\mathbf{u}|}$. The tensor components depend on the gas velocity [12,13]:

$$D_p = 1.5d_0|\mathbf{u}|; \quad D_t = 0.3d_0|\mathbf{u}|. \quad (10)$$

The heat conductivity was calculated by the formula $\Lambda = \lambda_g \mathbf{I} + c_p \rho_g \mathbf{D}_d$.

The heat conductivity of the solid phase with account for radiation heat transfer was calculated by the formula from [14]:

$$\lambda = \lambda_s + \frac{16}{3} \left(\frac{0.666m}{(1-m)} \right) \varepsilon \sigma d_0 T_s^3. \quad (11)$$

The coefficient of volumetric gas–solid heat transfer was calculated from the formula of [12]:

$$\alpha_{vol} = \frac{\lambda_g 6(1-m)}{d_0^2} \left[2 + 1.1 \text{Pr}^{1/3} \left(\frac{\rho_g u_g d_0}{\mu} \right)^{0.6} \right]. \quad (12)$$

The evaporation rate per volume unit was evaluated from:

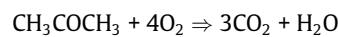
$$I_{ev} = \frac{3(1-m)c_w}{d_0 c_{w,0} \sqrt{2\pi \frac{RT_s}{M_w}}} (p_{sat} - p). \quad (13)$$

The saturated vapor pressure was calculated by a semiempirical formula:

$$p_{sat} = p_0 \exp(-a(1/T - 1/T_{boiling})), \quad (14)$$

where $a = 4935 \text{ K}$ was found by approximation of experimental data for the temperature interval from 75 to 125 °C.

A simple one-reaction chemical mechanism of acetone combustion was used in the calculations:



It was suggested that the reaction is of first order for acetone and oxygen. The numerical values of the activation energy and of the pre-exponential factor were taken from [15].

The 2DBurner software package [16] was used for the numerical solution of the two-dimensional problem.

4. Model verification

The gained experience in numerical investigations of the filtration combustion systems shows that verification of the model is necessary for reliable simulation [17]. This is connected with a large number of imperfectly defined parameters [10] and, first of all, the parameters of the model of chemical kinetics. To verify the computational model, we used experimental data of [5] on a stationary temperature field inside a reactor (Fig. 1). The flow rates of the components were fixed: $G_{\text{air}} = 0.0854 \text{ kg/m}^2/\text{s}$, $G_{\text{liq}} = 0.0221 \text{ kg/m}^2/\text{s}$, acetone concentration was $c = 0.284$. The scarce body of experimental data is due to the fact that the major part of temperature measurements was taken in nonstationary modes. Numerical reproduction of such modes is problematic because of the unknown temperature history of the system.

The geometrical parameters of the experimental reactor are shown in Fig. 2. The power of the heater is $P = 400 \text{ W}$, its length is 0.07 m, the inner radius is 0.026 m, and the outer radius is 0.031 m. The packed bed consists of 5-mm-diameter alumina balls.

The temperature profiles calculated along the characteristic streamline of experimental reactor (Fig. 1), as well as the measured values of temperature are presented in Fig. 2.

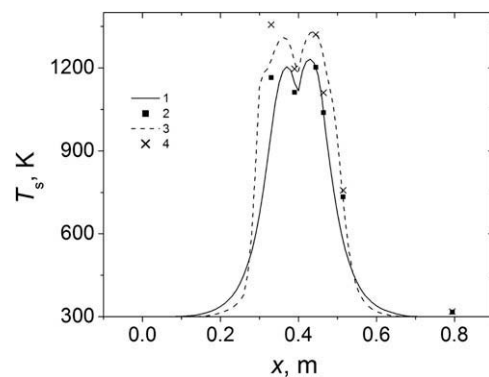


Fig. 2. Temperature of the solid phase along the streamline. 1, 3 – calculation; 2, 4 – experimental data. 1, 2 – $G_{\text{liq}} = 0 \text{ kg/m}^2/\text{s}$; and 3, 4 – $G_{\text{liq}} = 0.0221 \text{ kg/m}^2/\text{s}$, acetone concentration $c = 0.284$, time from the beginning of the liquid feeding 22 min. $G_{\text{air}} = 0.0854 \text{ kg/(m}^2 \text{ s)}$, $P = 400 \text{ W}$.

A comparison of the experimental and simulated data shows their reasonable agreement. Small discrepancy in the temperature (20–30 K) can be attributed to the uncertainty of the location of thermocouples, the natural inhomogeneity of a porous medium, the inaccuracy of thermodynamic data for a porous medium and insulation layer.

5. Results and discussion

The parameters that characterize the system considered can be divided into two groups: (1) geometrical and design parameters; (2) operationally varying parameters. The first group of parameters: reactor length, reactor diameter, size of packed bed particles, insulation layer thickness (i.e., the extent of thermal insulation). The second group of parameters is the flow rates of the working species: air, water, and organic component contained in water. Confining this investigation to stoichiometric mixtures of organics and oxidizer, we keep only two independent parameters. Here, for technical reasons we selected the liquid flow rate G_{liq} (kg/m²/s) and mass fraction of the organic component in water as the primary independent parameters. The air flow rate will be determined from the appropriate stoichiometric interrelation:

$$G_{\text{air}} = \frac{4(M_{\text{O}_2} + 3.76M_{\text{N}_2})G_{\text{liq}}C}{M_{\text{C}_3\text{H}_6\text{O}}} = 9.458G_{\text{liq}}C. \quad (15)$$

The values of the system parameters adopted to simulate the “standard” reactor are presented in Table 1.

The considered system is characterized by a specific behavior at ignition due to its three-phase nature. It was indicated in [5] that the initial heat of ignition of the reactor was considerably higher than that of the reactor with a combustible gas mixture. A physical analysis of the reasons for such a behavior was not conducted. We simulate the unsteady temperature field at the reactor startup. The temporal behavior of the front position and maximum temperature in the reactor are presented in Fig. 3. Two cases are considered. The first is characterized by a higher energy of ignition (length of preheated zone $L_{\text{ph}} = 5$ cm, $T = 1373$ K) and the second is characterized by a lower energy of ignition ($L_{\text{ph}} = 3$ cm).

The decrease in the maximum temperature observed during the first 90 s, is attributed to thermal relaxation of the hot area due to heat conductivity and convection. The duration of this period is two orders of magnitude higher than the same for filtration combustion of gaseous mixtures. It is connected with the low velocity

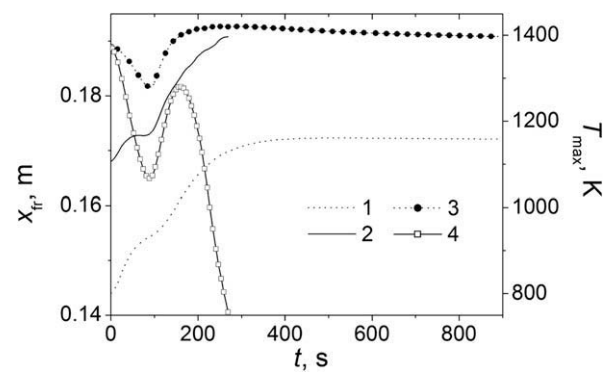


Fig. 3. Dependence of the front position (1, 2) and a maximum solid phase temperature (3, 4) at the reactor axis on time. Time starts at the beginning of liquid feeding. Reactor length is 20 cm, length of the preheated zone: (1, 3) 5 cm; (2, 4) 3 cm. Other parameters have standard values.

of liquid motion through the porous medium. The long time of hot area thermal relaxation is the physical reason for the higher value of the initial energy input necessary for ignition of the filtration combustion of liquid. The subsequent rise in temperature (Fig. 3) is due to the release of combustion heat. Curves 1 and 2 correspond to the establishment of a steady-state combustion regime, and the system cools down correspondingly.

Typical temperature profiles along the axis of the reactor corresponding to steady-state combustion of water-dissolved organics are presented in Fig. 4.

The combustion front is clearly defined. The decrease in the temperature behind the front is due to heat losses of the system.

We carry out a parametric study of the system with respect to the liquid flow rate and constructive parameters of the reactor. The standard values of the parameters are presented in Table 1. The air flow rate is defined by stoichiometric correlation with the flow rate of the combustible component in all calculations.

A maximum temperature in the reactor and the combustion front position are important parameters in the design of practical devices; they particularly define the quality of refractory materials. The named parameters are presented in Fig. 5 as a function of the liquid flow rate. The presented data show that the temperature is brought to saturation at about 2000 K. This temperature corresponds to the adiabatic combustion temperature of a water–organic mixture at the standard value of concentration. The character of the correlation $X_{\text{fr}} = f(G_{\text{liq}})$ is similar to that of gas filtration combustion [9] and is explained by the linear growth of the recuperated heat with the downstream shift of the front. Really the

Table 1
Standard system parameters.

Description	Symbol	Value
Specific heat capacity of the packed bed material	c_s	1000 J/(kg K)
Packed bed material density	ρ_s	1250 kg/m ³
Porosity	m	0.4
Reactor size		
Length	L	0.4 m
External tube diameter	d_2	0.07 m
Internal tube diameter	d_1	0.04 m
Internal tube length	l	0.38 m
Liquid density	ρ_w	1000 kg/m ³
Size of solid particles	d_0	5 mm
Specific flow rate of liquid	G_{liq}	0.1 kg/(m ² s)
Mean liquid velocity	u_w	1.4 mm/s
Concentration of liquid in the solid phase at the inlet	$c_{w,0}$	71 kg/m ³
Concentration of acetone in liquid	c	0.4
Temperature of incoming air and the ambient	T_0	300 K
Coefficient of heat exchange with the ambient	α	4 W/(m ² K)
Specific flow rate of air	G_{air}	Stoichiometric
Pressure at the outlet	p_0	1 atm

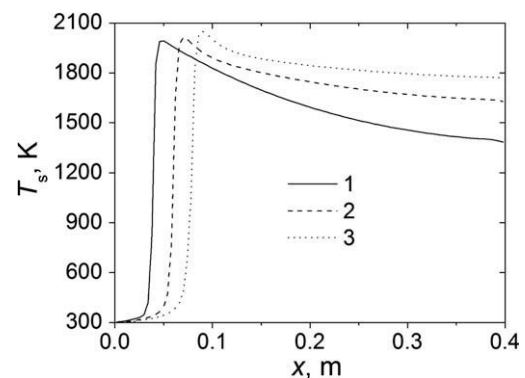


Fig. 4. Gas temperature along the reactor axis. Specific flow rate of liquid: (1) 0.2 kg/(m² s), (2) 0.35 kg/(m² s), and (3) 0.5 kg/(m² s). Other parameters have standard values.

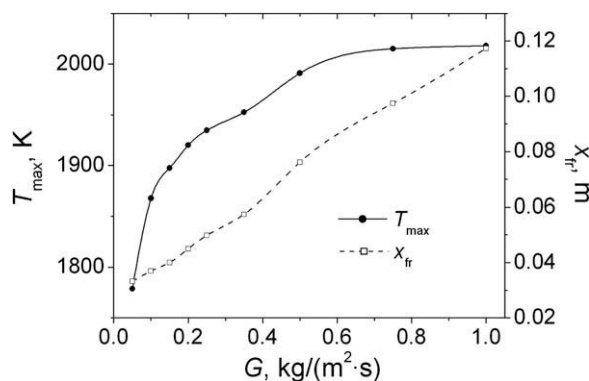


Fig. 5. Maximum temperature at the front and front position as functions of the liquid flow rate. Other parameters have standard values.

surface of heat transfer from the combustion products to the incoming mixture increases with front displacement.

The influence of the concentration of organic components in water on the parameters of the combustor operation is probably the most important information from the viewpoint of practical utilization of the process for purification of polluted water.

Fig. 6 demonstrates variation of the maximum temperature and of the front position with a change in the concentration of organics in the liquid. The increase of temperature at the combustion front is associated with the increase of heat content of the working mixture. As the temperature increases, so does the intensity of heat recirculation, which results in the shift of the combustion front towards the entrance.

One of the essential tasks of this research is the determination of the MCL for self-sustained operation of the reactor. The value of the MCL was estimated as a result of the following procedure. For the given parameters a steady-state solution for the temperature and concentration field is obtained, after which the concentration of acetone in the water solution is reduced by 2%. If a steady state is reached for a new value of concentration, it is reduced again unless the combustion is extinguished. Thus the value of MCL is determined with an accuracy of about 1%.

From the viewpoint of physics, the value of MCL is determined by heat losses of the system and capability of heat recirculation. We investigate the MCL correlation with the constructive parameters of the reactor. The dependence of the minimum concentration limit on the length of the system is presented in Fig. 7 for different sizes of particles. The length of the internal tube as well as the length of the “dead end” gap were proportional to the system

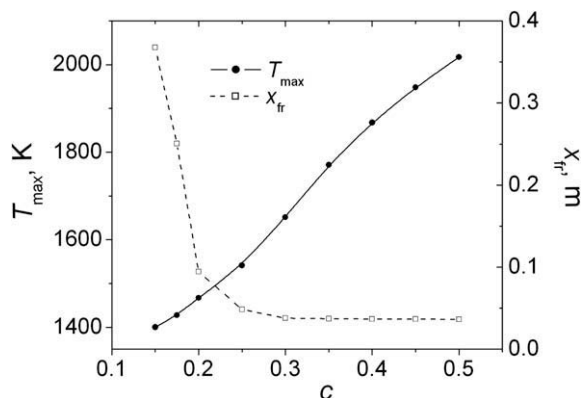


Fig. 6. Maximum temperature and combustion front coordinate as functions of acetone concentration. Other parameters have standard values.

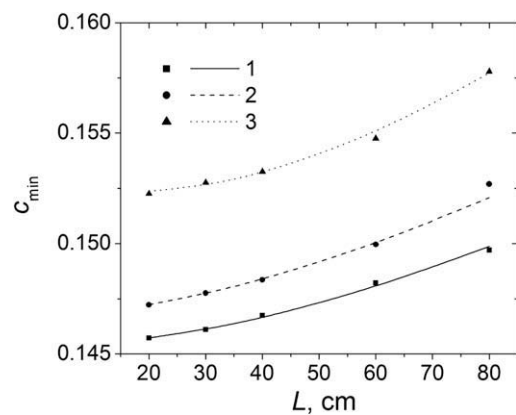


Fig. 7. Minimum concentration limit of acetone content in water as a function of the reactor length. Size of packed bed particles: (1) 0.25 cm, (2) 0.5 cm, and (3) 1 cm. Other parameters have standard values.

length. The size of particles primarily influences the dispersion heat and mass transfer coefficient, radiative heat transfer coefficient, and specific surface area of the porous medium. From the viewpoint of secondary effects, the larger particles provide an increase in the width of the combustion front and its shift towards the entrance of the reactor, intensify heat transfer both to the incoming fluid and external surface of the device. The integral effect of the increase in the size of particles, i.e., the growth of the MCL (Fig. 7) is similar to the case of filtration combustion of gaseous fuels [18].

The growth of the MCL with the system length is an unexpected effect at first sight. It is explained by the increase of the “dead end” zone of the reactor together with the length of the system. Indeed, heat from the “dead end” zone basically goes to the environment and cannot be recirculated. To confirm this notion, we performed similar calculations with a constant length of the “dead end” zone of the reactor, Fig. 8. One can see that the functional dependence $c_{\min} = f(L)$ in the latter case acquires a different character, comprehensible from the physical viewpoint. Another result of the simulation is the evident saturation of the MCL curves at the reactor length $L = 40$ – 60 cm.

Simulations of the MCL presented above demonstrate the integral influence of the heat recirculation and heat losses factors. To consider the latter factor separately, we built the $c_{\min} = f(L)$ correlations for the system with different effective heat transfer coefficients $\alpha = 0, 2, 4, 8, 12$ W/(m² K), Fig. 9. The length of the “dead

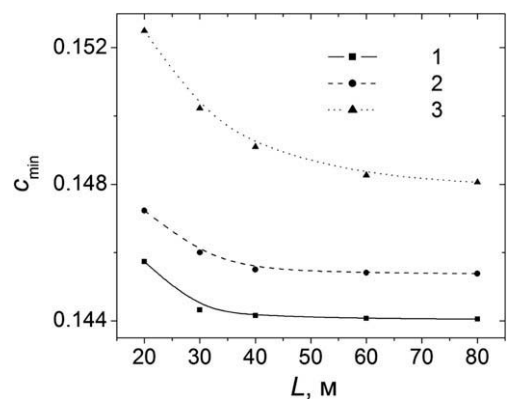


Fig. 8. Minimum concentration limit of acetone content in water as a function of the reactor length. Size of packed bed particles: (1) 0.25 cm, (2) 0.5 cm, and (3) 1 cm. Constant length of the “dead end” zone. Other parameters have standard values.

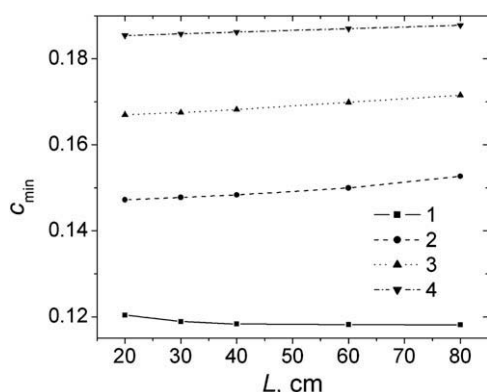


Fig. 9. Minimum concentration limit of acetone content in water as a function of the reactor length. Heat transfer coefficient: (1) $\alpha = 0$; (2) 4; (3) 8; and (4) 12 W/(m² K). Other parameters have standard values.

Table 2

Correspondence of the heat transfer coefficient to the parameters of the refractory layer.

Refractory layer thermal conductivity (W/(m K))	Refractory layer width L (cm)	α (W/(m ² K))
0.15	6.72	4
0.15	2.48	8
0.15	1.50	12

end” zone was proportional to the length of the reactor. Correspondence of the heat transfer coefficients to the physical parameters of the refractory layer of the reactor is illustrated in Table 2 (radius of the reactor has a standard value, see Table 1).

The data presented in Fig. 9 demonstrate a strong influence of the effective heat transfer coefficient (refractory layer width) on the MCL. The dependence of the MCL on the reactor length is poorly expressed in comparison with the dependence on the heat transfer coefficient. As expected, the MCL decreases with the length in the adiabatic case. This tendency is very weak as far as thermal relaxation of the exhaust gas (heat exchange with the incoming gas) acquires an exponential character. From this standpoint, regenerative (reverse flow) filtration combustion reactors may demonstrate considerably better performance.

6. Conclusions

The new technology of water purification of organic inclusions or solutes by means of filtration combustion is substantiated and investigated numerically. The essence of the technology is in simultaneous evaporation of a liquid and combustion of organic components within an inert porous medium of a recuperative reactor (“tube-in-tube” type). Acetone solution in water was used as a model liquid.

The standard model of filtration combustion based on heat and mass conservation equations for a porous medium and the gas phase, taking into consideration chemical reactions in the gas phase was used. The standard model was supplemented with the equation of mass conservation for the liquid phase and phase transition. The model was verified on the basis of the experimental data of thermometric measurements of the system [5]. Two-dimensional simulation of the system is performed.

The physical reason for the comparatively high energy consumption at the reactor startup was revealed. It is attributed to the fact that transportation of the liquid to the initially preheated zone takes much more time (two orders of magnitude) compared to transportation of a gaseous fuel. During the time of transporta-

tion the maximum temperature decreases due to thermal relaxation and this results in the comparatively higher energy input necessary for combustion ignition. In the case where ignition occurs, a steady-state regime with the fixed position of the evaporation and combustion zones has been established.

The general characteristic features of the dependence of the temperature and front position on the multiphase flow rate are similar to those of the gas filtration combustion, explored earlier [9]. The temperature grows with the flow rate, with a clear tendency to saturation, while the front position shifts to the end of the reactor linearly.

The minimum concentration limit is one of the most important characteristics of the system that practically defines the area of application of this technology. Indeed, water with a low concentration of organic components is the most complicated object for recovery. On the other hand, oxidation purification of such a system may be effective. The minimum concentration limit as a function of the length of the reactor, size of packed bed particles, and of the heat transfer coefficients was investigated. The concentration limit grows with increase in heat losses or the size of particles. Most strongly the concentration limit depends on heat losses.

The influence of the “dead end” zone length of the reactor on the minimum concentration limit has been revealed. In the calculations in which the “dead end” length was increased proportionally to the total length of the reactor, the value of the minimum concentration limit grew with the reactor length in spite of the growth of efficiency of heat recirculation. It was demonstrated that this effect is connected with heat losses associated with the “dead end” of the reactor. In the case of a constant length of the “dead end” zone, longer reactors provide a better minimum concentration limit. At the same time, an increase in the reactor length over some definite value (in the simulated case $L \sim 50$ cm, Fig. 8) is ineffective, since heat recirculation is limited by heat losses to the environment. From this viewpoint, bigger reactors with massive heat insulation may provide a better MCL.

Taking into consideration the poor possibilities of scaling up of the “tube-in-tube” reactors, investigation of the water recovery system that utilizes a regenerative filtration combustion reactor is very interesting for the future.

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