

Combustion and Atmospheric Pollution

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The book includes 128 revised, edited and formatted condensed papers on combustion science and technology and physical chemistry of atmospheric pollution written by international experts from 17 countries. It covers fundamentals of combustion in propulsion devices, ground transportation engines, and stationary power plants with an emphasis on pollutant emission problems, pollutant formation chemistry, physics and chemistry of exhaust-related clusters and aerosols, and assessment of accompanying environmental effects. The book is published in connection with the International Symposium on Combustion and Atmospheric Pollution held in St. Petersburg, Russia, July 8–11, 2003, dedicated to the memory of N.N. Semenov.

The volume is addressed to practicing engineers and researchers and can serve as a reference book for graduate studies in combustion science, technology, and environmental protection.

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FILTRATION COMBUSTION OF GASES AT HYDROCARBON DESORPTION FROM POROUS MEDIA

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Introduction

The problem of recycling and incineration of industrial wastes becomes increasingly acute. One of typical problems is recreation of catalysts, sorbents, and other materials containing sorbed combustible components, for example, zeolite sorbents used for transformer oil cleaning [1]. Recreation of such materials may be performed in a filtration combustion (FC) wave. Compared to thermovacuum zeolite cleaning this method allows removal of solid organic sediments.

The idea of using thermal waves for recycling porous materials is not new. Thermal waves are applied for recreation of some types of catalysts. When a considerable amount of combustible component is desorbed, some specific FC regimes can occur. Such regimes are worth of theoretical and experimental investigation. The publications on this subject deal mainly with aerosols [2] and combustion of liquids, in particular, combustion of monofuels (hydropzine) [3] in a porous medium.

In this work, the experimental and theoretical investigations of gas filtration combustion with hydrocarbon desorption from a porous skeleton are reported. The influence of water on the combustion wave propagation velocity and maximum temperature is explored. Based on the investigation, the recommendations for effective and ecologically clean zeolite sorbents recreation process (and similar processes) have been formulated.

Experiments

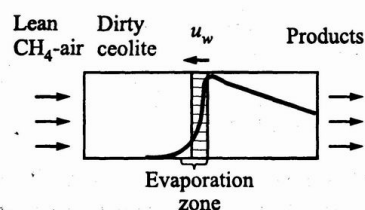


Figure 1 Schematic of the experiment

The oxidation of ceolite sorbed organics was investigated experimentally. The regime of counter-flow flame propagation was used as a working regime to obtain a minimal temperature in the front and provide permanent feed of organic vapors to the combustion front and their complete oxidation (at sufficient amount of oxygen), Fig. 1. If the oxygen content is not sufficient, unburned

organics will most probably be reabsorbed in ceolite, which has already been partly or completely recreated. In the co-flow wave propagation regime, organics vapors evacuate from the combustion front.

The experimental setup consists of a gas feed system and quartz tubular reactor 7 cm in diameter and 40 cm long. Packing is formed of ceolite particles of porosity $m = 0.4$. Spark ignition is used. Along the axis, a capillary is introduced with a movable thermocouple inside it. Mass content of sorbed oils and water was estimated as $\chi \cong 0.1$ and $\psi \cong 0.054$, respectively. Some experimental results are presented in Table 1.

In experiment 3, in spite of lower flowrate, the FC front propagation speed is higher because of the optimal fuel-air ratio in the input gas mixture. In experiments 1, 2, and 4, the cycling of wave parameters was observed: when the front reached the unburned ceolite layer, the

Table 1 Experimental results

Experiment No.	Air flowrate, l/h	Natural gas flowrate, l/h	Φ	u_w , cm/h	$T_{s,m}$, K
1	1000	75	0.73	-10	1300
2	1000	50	0.45	-12	1380
3	1000	23	0.18	-18	1400
4	1000	80	0.75	-10	1220

temperature dropped due to fuel excess, but some time later, after a part of fuel is burned, the front heats up and accelerates.

The influence of water addition to the porous medium for the aim of maximum temperature control was also investigated.

Numerical Study

The standard set of equations for FC simulation [2-4] was used. The source terms representing methane combustion heat release due to oil combustion, Q_2 , and heat consumption due to oil and water evaporation, Q_3 :

$$\rho_g \frac{\partial T_g}{\partial t} + c_{p,g} G \frac{\partial T_g}{\partial x} = Q_1 + \frac{\partial Q_2}{\partial t} + \frac{\partial Q_3}{\partial t} + \alpha_V (T_s - T_g) \quad (1)$$

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

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

where ρ_g is the density, kg/m³; T is the temperatures; c is the heat capacity, kg/m³; α_V is the heat exchange coefficient, W/(m³·K); ε is the porosity; λ_s is the heat conductivity coefficient, W/(m·K); A is the dimensionless fuel concentration; K is the reaction preexponential factor, s⁻¹; E is the reaction activation energy, J/mol; R is the gas constant, J/(mol·K); and indices g denote to gas, s — to solid, 1 — to methane, 2 — to oil, and 3 — to water.

The condition of oxygen deficit in the system is expressed as a condition of oil evaporation rate, G_2 , exceeding its critical value, G_2^* :

$$G_2 > G_2^*, \quad G_2^* = \frac{GC_2(1 - \Phi)}{v_n \rho_{g,0}} \left(\frac{F}{A} \right)_{st,2} \quad (4)$$

The burnout degree of condensed organics is found by using parameter χ'_M :

$$\chi'_M \equiv \frac{G_2^*}{|u_w| \rho_s (1 - \varepsilon) \chi_m} \quad (5)$$

where u_w is the combustion wave front velocity, m/s.

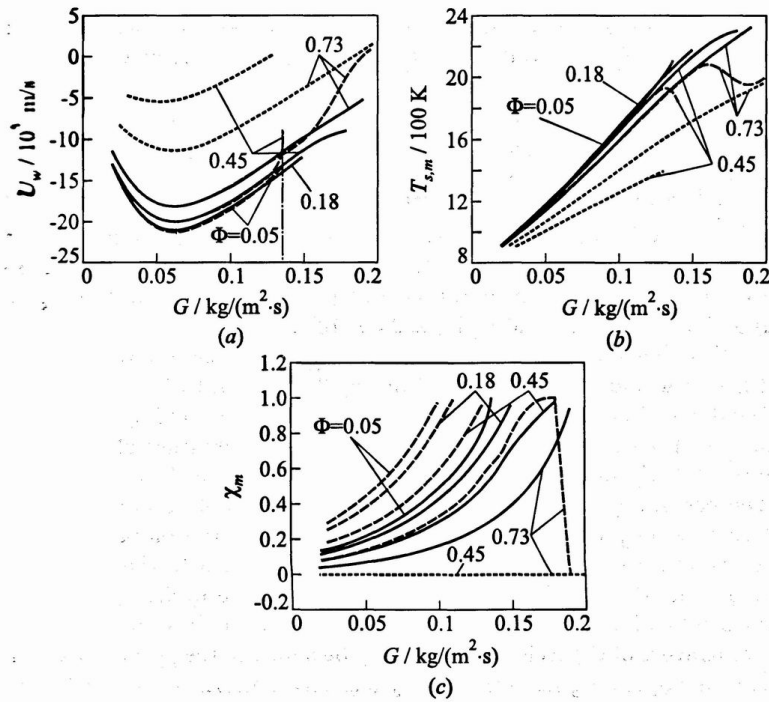


Figure 2 Predicted dependencies of u_w , $T_{s,m}$, and χ'_M on the total flowrate, G , at different Φ and χ_m

In general, $\chi'_M \leq 1$ ($\chi'_M = 1$ in the complete oxidation case).

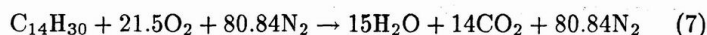
To simplify calculations, the analytical solutions of the FC theory may be used [5]:

$$T_{s,m} \cong \frac{\Delta \tilde{T}_a}{1+a} + \frac{E}{R \ln(\varepsilon c_{p,g} \rho_{g,0} T_0 K (1+a) / (\alpha_V \Delta \tilde{T}_a))} \quad (6)$$

where $a = (1-\varepsilon)\lambda_s \alpha_V / (c_{p,g} G)^2$ is the dimensionless parameter.

The system of governing equations was solved for the following set of parameters: $\varepsilon = 0.49$, $c_s = 794 \text{ J}/(\text{kg} \cdot \text{K})$, $\rho_s = 3.15 \cdot 10^3 \text{ kg}/\text{m}^3$,

$c_{p,g} = 1.3 \cdot 10^3 \text{ J/(kg}\cdot\text{K)}$, $\lambda_{s,0} = 1.0 \text{ W/(m}\cdot\text{K)}$, packing particle diameter $d = 6 \text{ mm}$, $(F/A)_{st,1} = 0.11$, $E = 1.3 \cdot 10^5 \text{ J/(mol}\cdot\text{K)}$, $K = 2.6 \cdot 10^8 \text{ s}^{-1}$. It was assumed that heat of oil desorption is negligible compared to the heat of oil combustion, i.e., $H_{2,d} \ll H_2$. The oil was modeled by *n*-tetradecane ($\text{C}_{14}\text{H}_{30}$), with the overall oxidation equation:



For modeling of $\text{C}_{14}\text{H}_{30}$ oxidation, the following parameters were adopted: $(F/A)_{st,2} = 1.0 \cdot 10^{-2}$, $H_2 = 5.1 \cdot 10^7 \text{ J/kg}$, and $C_2 = 198 \cdot 10^{-3} \text{ kg/mol}$. Water evaporation heat (with regard for its heating to 100°C) was taken equal to $H_3 \cong 2.55 \cdot 10^6 \text{ J/kg}$.

The dependencies of u_w , $T_{s,m}$, and χ'_M of the total flowrate, G , at different Φ and χ_m are presented in Fig. 2. As seen, the FC waves with fuel desorption exhibit higher propagation velocities and higher temperatures. The principal feature of the curves is the evidence of transition from FC without additional fuel to FC with desorbed oil ($\chi'_M \sim 1$). The beginning of this transition coincides with the beginning of counterflow wave propagation. The nonmonotonous variation of maximum temperature with the flowrate (Fig. 2b) corresponds to this transition area. The data of Fig. 2 explain qualitatively the cyclic dynamics of the combustion wave observed experimentally. To reduce the maximum temperature of the skeleton, water may be added to the porous medium. The corresponding numerical study has been performed.

Concluding Remarks

The experimental and numerical investigations show that at a proper choice of parameters, a complete oxidation of sorbate may be achieved during FC. The maximum temperature of the process may also be controlled. The process under study may be applied for catalyst recreation, sorbent recycling, etc.

References

1. <http://www.etma.com.ua/products/ps-1.html>.
2. Martynenko, V. V., R. Echigo, and H. Yoshida. 1993. Modeling of liquid droplet fuel combustion in inert porous media. *Int. J. Heat Mass Transfer* 36(13):3201-9.

3. Koshkin, B. Yu., V. A. Bunev, V. S. Babkin, and Yu. M. Laevsky. 1995. The decomposition flame of hydrozine in inert porous media. *Combustion Flame* 103:143–50.
4. Laevskii, Yu. M., and V. S. Babkin. 1988. Propagation of thermal waves in heterogeneous media. Ed. Yu. Matros. Novosibirsk. 108–45.
5. Dobrego, K. V., and S. A. Zhdanok. 1009. Calculation of filtration combustion performance based on two-temperature one-dimensional model. *Eng. Physical J.* 71(3):424–31.

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