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Unsteady Combustion of Gases in an Inert Porous Layer

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Unsteady filtration combustion of gases in an inert porous layer is considered taking into account the gas pressure distribution in the pores. The steady-state combustion limits in the layer as functions of depending on gas flow and parameters of interfacial heat transfer were determined. The possibility of the existence of self-oscillating filtration combustion is shown.

Key words: filtration gas combustion, interfacial heat transfer, self-oscillating combustion.

INTRODUCTION

Development of powerful SHS converters involves the use of filtration combustion of gases. The filter element of the setup — converter — is a porous ceramic-metal tube or a plate mounted in a standard gas burner. The porous material is SHS ceramics based on nickel and aluminum compounds with known thermophysical and structural properties. Due to energy concentration in the porous layer, the converter provides efficient combustion of natural gas and other hydrocarbons and thermal energy transfer by radiation.

The development of existing and new SHS converters aimed at increasing the radiation power is inextricably related to studies of modes and structure of the wave of filtration combustion of gases in an inert porous medium. Due to the diversity physicochemical processes and the large number of parameters affecting the filtration combustion mechanism and mode, along with the structural features of the burner itself, mathematical modeling as an effective method of theoretical study. Mathematical models for filtration combustion of gases and condensed materials are based on the equations of the mechanics of multiphase media supplemented with the equations of chemical kinetics [1]. A fairly complete review of experimental and theoretical studies of filtration gas combustion in inert porous media is presented in [2]. Numerical two-dimensional calculations of temperature and concentration fields supported experimentally have been performed [3] for combustion of a methane–air mixture in a rectangular burner with an inert coarse-pore section. Unsteady filtration flow of a stoichiometric gas mixture through a porous layer obeys Darcy's law and is determined by both on the pressure gradient at the outer boundaries of the layer and the pressure distribution in the layer. In some studies, it is assumed that the gas flow rate is constant [4–6], which allows one not to consider the equation of motion of the gas. Initiation of combustion for devices based on the mechanism of filtration gas combustion is carried out at the outlet of the gas flow from the porous layer by pulsed conductive supply of heat or a pilot flame to the outer surface of the porous bed — ignition toward the flow. The condition of constant gas flow rate during ignition is not satisfied at a high rate of external heating and low gas permeability of the condensed material.

In the theory of filtration combustion [1, 7], heterogeneous systems are described by two approaches — one-temperature and two-temperature. In the modeling of filtration combustion of metals with the formation of condensed reaction products [8], the one-temperature approximation is used, as a rule, which is due, on the one hand, to strong interfacial heat transfer and the developed interface, and, on the other hand, to the occurrence of a heterogeneous chemical reaction. Filtration gas combustion is characterized by weaker interfacial heat transfer and a significant difference in temperature between the solid and gas phases. In studies of

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filtration gas combustion, two-temperature models are preferred.

In this work, we propose a two-temperature model for gas combustion in an inert flat porous layer which takes into account the gas pressure distribution in the pores. The aim of the study is to determine the modes of filtration gas combustion in a porous layer of finite thickness with variation in the gas flow rate, layer thickness, and interfacial heat transfer parameters.

MATHEMATICAL MODEL

The mathematical formulation of filtration gas combustion in an inert porous medium in dimensionless form is given by the system of equations

$$\frac{\partial\theta_c}{\partial\tau} = (1-m)^{-1}\frac{\partial}{\partial\xi}\left((1-m)\frac{\partial\theta_c}{\partial\xi}\right) - B_c(\theta_c-\theta_g); \quad (1)$$

$$\frac{\partial\theta_g}{\partial\tau}+v_g\frac{\partial\theta_g}{\partial\xi}=\rho_a\exp\frac{\theta_g}{1+\mathrm{Ar}\theta_g}+B_g\frac{1-m}{m}(\theta_c-\theta g); \quad (2)$$

$$\frac{\partial}{\partial\tau}(m\rho_i)+\frac{\partial}{\partial\xi}(m\rho_i v_g) = \mathrm{Td}\rho_a\exp\frac{\theta_g}{1+\mathrm{Ar}\theta_g}; \quad (3)$$

$$\frac{\partial}{\partial\tau}(m\rho_a)+\frac{\partial}{\partial\xi}(m\rho_a v_g) = -\mathrm{Td}\rho_a\exp\frac{\theta_g}{1+\mathrm{Ar}\theta_g}; \quad (4)$$

$$P = \rho_g(1+\mathrm{Ar}\theta_g); \quad (5)$$

$$v_g = -\mathrm{Pe}_f\left(\frac{m}{1-m}\right)^2\frac{\partial P}{\partial\xi}; \quad (6)$$

$$\rho_g = \rho_a + \rho_i \quad (7)$$

with the initial and boundary conditions

$$\xi = 0:\quad \theta_c = \theta_w\ (\tau < \tau_w);\qquad \frac{\partial\theta_c}{\partial\xi} = 0\ (\tau > \tau_w), \quad (8)$$

$$\xi = L:\quad \frac{\partial\theta_c}{\partial\xi} = \mathrm{Bi}(\theta_c-\theta_0),\ \theta_g = \theta_0,\qquad \rho_a = \rho_n,\quad \rho_i = 0, \quad (9)$$

$$\tau = 0:\quad \theta_c = \theta_0,\quad \theta_g = \theta_0,\qquad \rho_a = \rho_0,\quad \rho_i = 0. \quad (10)$$

The dimensionless variables and parameters have the form

$$\theta_c = \frac{T_c-T_*}{RT_*^2}E;\quad \theta_g = \frac{T_g-T_*}{RT_*^2}E;$$

$$\theta_0 = \frac{T_0-T_*}{RT_*^2}E;\quad \theta_w = \frac{T_w-T_*}{RT_*^2}E;$$

$$\tau = \frac{t}{t_*};\quad \tau_w = \frac{t_w}{t_*};\quad \xi = \frac{x}{x_*};$$

$$\rho_a = \frac{\rho_{\mathrm{ac}}}{\rho_g^*};\quad \rho_i = \frac{\rho_{\mathrm{in}}}{\rho_g^*};\quad \rho_g = \frac{\rho}{\rho_g^*};$$

$$\rho_0 = \frac{\rho_a^0}{\rho_g^*};\quad \rho_n = \frac{\rho_a^n}{\rho_g^*};\quad p_* = \rho_g^* RT_*;\quad P = \frac{p}{p_*};$$

$$\mathrm{Td} = \frac{c_c RT_*^2}{QE};\quad t_* = \mathrm{Td}k_0\exp\left(-\frac{E}{RT_*}\right);$$

$$x_* = \sqrt{\frac{\lambda_c t_*}{c_c\rho_c}};\quad \mathrm{Ar} = \frac{RT_*}{E};\quad B_c = \frac{3\alpha t_*}{R_0 c_c\rho_c};$$

$$B_g = \frac{3\alpha t_*}{R_0 c_g\rho_g^*};\quad \mathrm{Bi} = \frac{\alpha_0 x_*}{\lambda_c};\quad L = \frac{l}{x_*};$$

$$v_g = \frac{vt_*}{x_*};\quad \mathrm{Pe}_f = \frac{k_f c_c\rho_c p_*}{\lambda_c}.$$

In the dimensionless quantities, the following dimensional variables were used: x and t are the coordinate and time, T_0, T_c, and T_g are the initial temperature and the temperatures of the condensed and gas phases, T_w and t_w are the temperature and time of action of the heated surface, ρ_c, ρ_g, ρ_{ac}, and ρ_{in} are the densities of the condensed phase, gas mixture, and the active and inert gases, ρ_a^0 and ρ_a^n are the gas density at the initial time and at the inlet to the porous layer (right boundary), m is the porosity, λ_c is the thermal conductivity of the condensed phases, c_c and c_g are the heat capacities of the condensed and gas phases, v is the gas velocity, p is the pressure of the gas mixture, Q is the heat effect of the reaction, k_0, E, and R are the preexponent, activation energy, and gas constant, k_f is the filtration coefficient, α, α_0 are the coefficients of interfacial and external heat transfer, R_0 is the characteristic pore size, and l is the layer thickness. The scaling temperature and the density of the gas mixture are set equal to $T_* = 1000$ K and $\rho_g^* = 0.7$ kg/cm^3, respectively. The dependence of the filtration coefficient on the porosity in Darcy's law (6) corresponds to the Kozeny–Kármán formula [9].

Problem (1)–(10) was solved numerically using an implicit scheme with finite differences against the flow on a spaced-apart difference mesh. Pressure, temperature, and density of the phases were calculated at the nodes, and the gas velocity was calculated between the mesh nodes. Approximating convergence was versified during the calculations on a sequence of refined meshes. In the calculations, the mass balance for the gas entering the pores from the ambient medium, the gas contained in the pores in the initial time, consumed gas, and the gas released in the chemical reaction was satisfied to within 1%.

STABILIZATION OF COMBUSTION INSIDE THE POROUS LAYER

The combustion wave formed at the outlet of the gas flow from the porous medium propagates into the

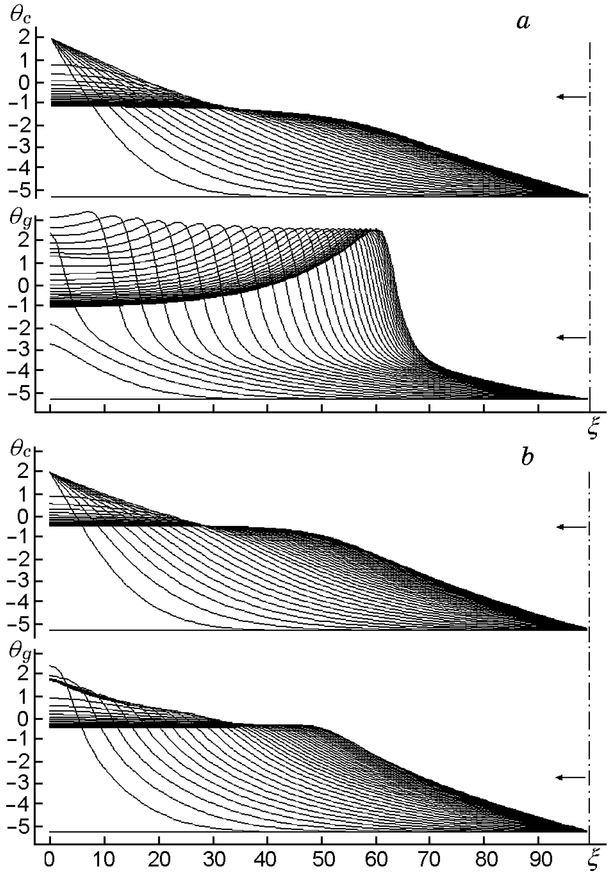

Fig. 1. Temperature distribution of the condensed and gas phases with an interval $\Delta\tau = 100$ — from ignition to steady-state combustion: dash-and-dotted line shows the right boundary of the layer; the arrows indicate the direction of the gas flow; $\theta_0 = -5.4$, Td = 0.156, Ar = 0.12, $L = 100$, $\mathrm{Pe}_f = 150$, $\theta_w = 2$, $\rho_0 = 4.4$, $\rho_n = 5$, $m_0 = 0.62$, $\tau_w = 1000$; (a) $B_c = 0.001$ and $B_g = 0.5$; (b) $B_c = 0.016$ and $B_g = 8$.

interior of the layer (Fig. 1). After switch-off of the external heating, the combustion wave is stabilized in the porous layer. At a low temperature of the condensed phase and a small thickness of the layer, the reaction of the gas mixture may be incomplete. The unburned portion of the mixture leaves the porous layer and can completely react already in the gas medium. Gas combustion outside the layer in the mathematical model is not considered. The steady-state mode of filtration gas combustion in the layer is in the process of establishment from the calculated temperature and concentration fields, which corresponds to the refinement of lines in Fig. 1. The modeling results agree qualitatively with experimental data. Quantitative comparison is difficult because of the absence of reliable data on the effective thermal and chemical constants.

Experiments were performed on a burner with a flat porous layer in the shape of a disk 80 mm in diameter and 30 mm thick; the pore size is 0.2 mm. A stoichiometric mixture of methane with air was used as fuel. The temperature combustion characteristics were recorded by Chromel–Alumel thermocouples attached to the outer surface and in the middle of the layer.

In the design of heat converters, it is important to study the scaling effect — the dependence of the operating parameters of the burner device (temperature, radiation flux, etc.) on its linear dimensions with the preservation of the gas flow rate and the initial temperature and composition of the gas mixture. For this purpose, calculations were carried out with variation in the thickness of the porous layer L and inversely proportional variation in the filtration coefficient (or pressure jump) to maintain the gas flow rate. The results of the numerical study show that varying the width of the layer over a wide range does not change the condensed-phase temperature at the outlet of the gas flow from the porous layer. Accordingly, there is no change in the intensity of the radiation flux. Constant gas flow rate implies a constant mass burning rate provided that the gas reacts in the porous layer completely. The structure of the combustion wave and the structure of the heat zone remain unchanged. As the thickness of the layer increases, so does the width of the post-reaction zone in which the temperatures of the condensed and gas phases are equal. As the thickness of the layer becomes smaller than the critical value, it is impossible to keep the combustion inside the layer. After switch-off of the external heating ($\tau > \tau_w$), the combustion zone is shifted down the flow with the combustion front moving beyond the layer boundaries, which, in the model, is accompanied by a decrease in the temperature of the porous bed to the initial temperature θ_0.

The results of numerical investigation of the effect of the interfacial heat coefficient on the change of in the structure of the combustion wave are presented in Fig. 1. The ratio of the volumetric heat capacities of the phases, along with the absolute values of the interfacial heat transfer parameters, is one of the parameters that determine the operation mode of the burner. In the case of intense interfacial heat transfer, the temperatures of the phases differ insignificantly and the temperature distribution over the length of the layer is monotonic. If the interfacial heat transfer is weak and (or) the porosity of the layer is high, the gas temperature in the combustion zone can be 1.5–2 characteristic intervals higher than the temperature of the condensed medium. The gas temperature Profile in this case is nonmonotonic, with the maximum corresponding to the combustion front. The temperature distribution in the condensed

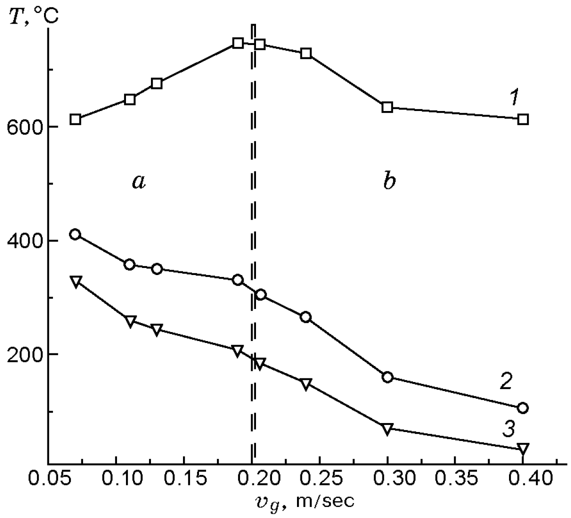

Fig. 2. Temperature of the condensed phase in steady-state combustion of stoichiometric methane–air mixture versus gas velocity (experiment): (a) combustion front is localized in the porous layer; (b) exit of the gas flame from the porous layer; 1) temperature of the condensed phase at the flow outlet; 2) at the center of the layer; 3) at the flow inlet.

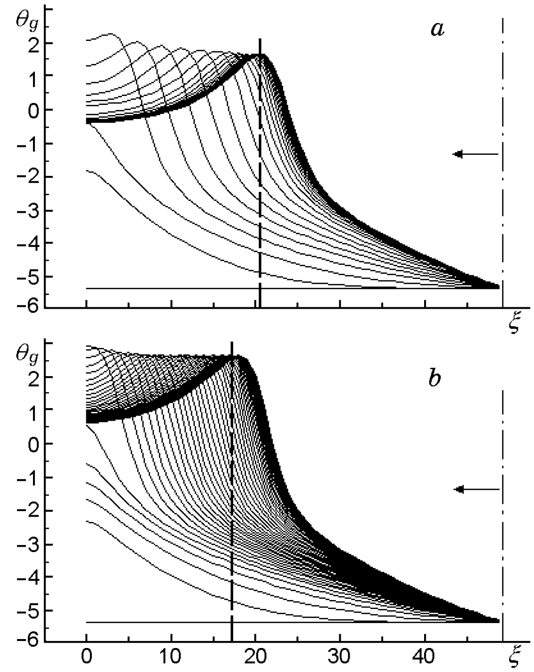

Fig. 3. Shift of the combustion zone with variation in the gas flow rate: the dot-and-dashed line shows the position of the combustion front; $\theta_0 = -5.4$, Td $= 0.15$, Ar $= 0.12$, $L = 50$, $B_c = 0.006$, $B_g = 3$, $\theta_w = 0$, $\rho_0 = 4.4$, $\rho_n = 5$, $m_0 = 0.65$; (a) Pe$_f = 60$ and $\tau_w = 800$; (b) Pe$_f = 85$ and $\tau_w = 1600$.

phase remains monotonic, as in the case of intense interfacial heat transfer, with the minimum temperature at the inlet and maximum temperature at the outlet of the gas from the layer. Stabilization of the combustion zone in the porous layer and the temperature of the porous bed at the outlet point of the flow $\xi = 0$ depend on the ratio and absolute values of the interfacial heat transfer coefficients B_c and B_g.

Measurements of the condensed-phase temperature show that as the gas flow rate increases with the stabilization of the combustion wave in the layer, the maximum of the porous medium increases and in the middle while the temperature at the center and at inlet to the layer decreases (Fig. 2). Numerical calculations lead to the following explanation for this effect for the case of weak interfacial heat transfer where the temperatures of phases in the reaction zone differ by 1–2 characteristic intervals and the flow rate is above the critical value. The critical flow rate dependent on the problem parameters determines the boundary below which combustion in the porous layer becomes impossible after switch-off of the external heating and the temperature tends to the initial value θ_0. With increasing gas flow rate, the location of the steady-state combustion front is shifted to the left of the flow (Fig. 3). The gas temperature in the combustion front grows because the mass burning rate increases. The latter two factors lead to an increase in the temperature of the condensed material at the outlet of the gas flow from the layer. Along with this, the temperatures of the gas and condensed phase at the center of the layer decrease as a result of intensification of convective heat transfer with increasing gas flow rate. A feature of the ignition at the flow outlet is that, with increasing gas flow rate, the external heating time τ_w needs to be increased to reach a steady-state combustion mode. The temperature of the condensed phase at the flow inlet is always higher than the gas temperature. The lower the gas velocity, the higher the excess. In the case of intense interfacial heat transfer, the temperature throughout the thickness of the porous layer increases with increasing gas flow rate, and it is not possible to explain the experimental data presented in Fig. 2. The foregoing is indirect evidence for the presence of weak interfacial heat transfer in the experiments corresponding to Fig. 2 because the gas temperature directly in the pores cannot be measured.

The numerical calculations showed the principal possibility of the existence of a self-oscillating mode of filtration combustion of the gas mixture (Fig. 4). The temperature of the phases at each point of the layer oscillates (with a higher amplitude for the gas phase) due to periodic displacements of the location of the combustion zone within the layer itself. The variations in the gas temperature and the heat release function

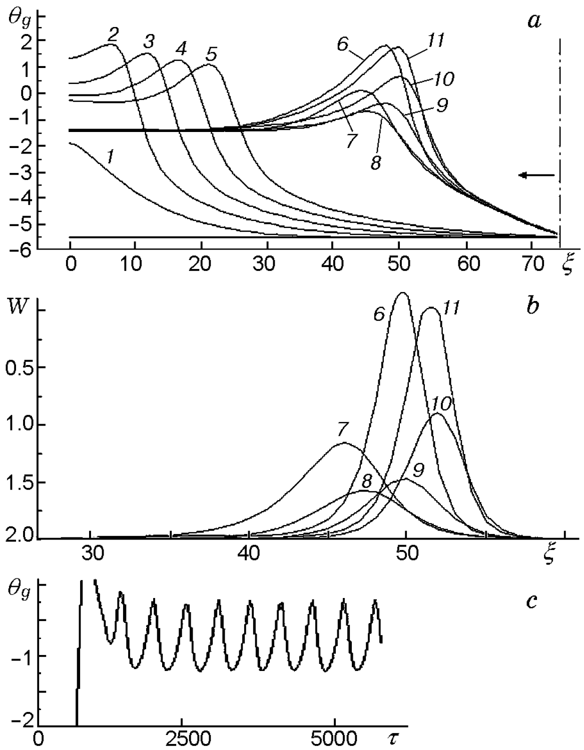

Fig. 4. Self-oscillating mode of filtration gas combustion: $\theta_0 = -5.5$, Td $= 0.125$, Ar $= 0.12$, $L = 75$, $\mathrm{Pe}_f = 75$, $B_c = 0.004$, $B_g = 2$, $\theta_w = 0$, $\rho_0 = 4.5$, $\rho_n = 5$, $m_0 = 0.62$, and $\tau_w = 800$; (a) gas temperature distributions; (b) distributions of the heat-release function W; (c) gas temperature in the middle of the layer versus time: $\tau = 200$ (1), 300 (2), 400 (3), 500 (4), 600 (5), 1500 (6), 1600 (7), 1700 (8), 1800 (9), 1900 (10), and 2000 (11).

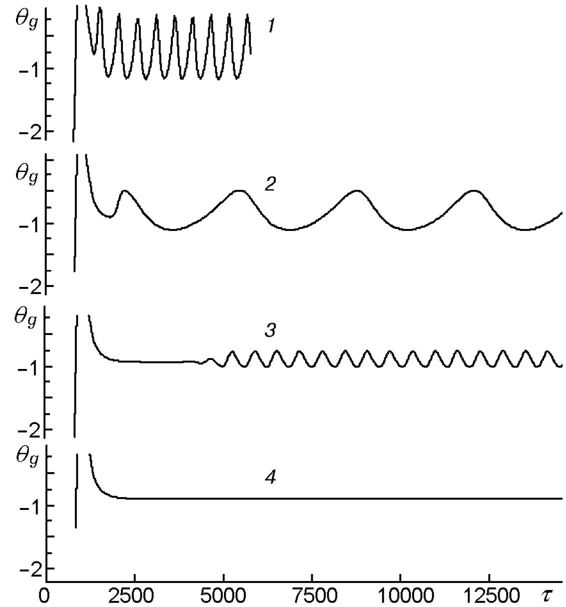

Fig. 5. Gas temperature dynamics at the center of the porous layer versus gas flow rate: $\theta_0 = -5.5$, Td $= 0.125$, Ar $= 0.12$, $L = 75$, $B_c = 0.004$, $B_g = 2$, $\theta_w = 0$, $\rho_0 = 4.5$, $\rho_n = 5$, $m_0 = 0.62$, $\tau_w = 800$, and $\mathrm{Pe}_f = 75(1)$, 80 (2), 85 (3), and 90 (4).

$W = \rho_a \exp \dfrac{\theta_g}{1 + \mathrm{Ar}\theta_g}$ during the first period of oscillations are described by curves 6–11 in Fig. 4. Oscillating modes have been observed previously in combustion experiments with a propane–air mixture in a channel of small diameter [10] and were due to the temperature gradient of the channel walls heated from outside. Flame with repetitive extinction and ignition (FREI) was numerically studied in [11], where it is shown that two differently directed chemical-reaction fronts can form in the hot part of the channel. The effective diameter of the channel (typical pore size) in a burner with a porous layer has the same range of values of 1 mm as the diameter of the channel in [10, 11].

When the combustion of the condensed phase reaches a steady-state or self-oscillating mode, a temperature distribution with the highest gradient in the inlet part of the porous layer is established. The gas mixture is ignited in the heated part of the layer, and the flame spreads against the gas flow. The temperature in the combustion front (the maximum of the heat release function) decreases, but complete extinction of the flame, as in [10], does not occur. Temperature oscillations have distinct structure and repetition (see Fig. 5). This mode of filtration combustion, as in the unsteady combustion of gasless systems [12], can be called self-oscillating. The observed mode is determined by the temperature gradient in the condensed phase, which depends on the gas flow rate and the parameters of interfacial and external heat transfer. As the consumption decreases, the amplitude and the oscillation frequency decreases. Temperature oscillations of the condensed phase with an amplitude not exceeding 10 °Cwere also recorded during the experiments but only for combustion of mixtures enriched with methane. An increase in the gas flow rate in a wide range of other parameters of the problem leads to stabilization of the combustion — transition from the self-oscillating to steady-state mode of burner operation.

CONCLUSIONS

Filtration combustion of gases in an inert porous layer of finite size was studied experimentally and theoretically with variation in the gas flow rate, interfacial heat transfer, and the thickness of the porous layer.

Conditions for the stabilization of the combustion front in the layer and its characteristics were determined. A self-oscillating mode of the gas combustion due to a decrease in the temperature gradient in the condensed phase with decreasing flow rate was found.

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