Journal of Applied Data Analysis and Modern Stochastic Modelling
Vol. 2 No. 1 (June, 2025)

CRITICAL DIAMETERS OF POROUS MEDIUM PARTICLES IN NON-ADIABETIC FILTRATION COMBUSTION OF METHANE-AIR MIXTURE

KABILOV M.M., KHALIMOV I.I., AND SHERMATOVA Z.B.

Abstract. The nonadiabatic case of propagation of a stationary wave of combustion of a methane-air mixture in an inert porous medium is considered. A large number of temperature profiles of porous medium and gas obtained by numerical solution of the problem are analysed. The realisation of phase temperature profiles satisfying the boundary conditions is taken as a basis for the existence of a low-speed stationary mode of wave propagation. For dangerous velocities of methane-air mixture blowing into a porous block, the boundaries of existence of a stationary mode of wave propagation on the plane of the porous medium particle diameter and heat transfer coefficient to the external medium are determined. The lower boundaries correspond to the minimum diameters of porous medium particles, and the upper boundaries correspond to the maximum diameters. At relatively high value of the heat transfer coefficient, the upper and lower boundaries intersect, and further, there is no stationary regime. With the decrease of the blowing rate of the mixture, the intersection points shift towards the decrease of the heat transfer coefficient, i.e. the area of existence of the stationary mode narrows and at the minimum blowing rate disappears. The effective pore diameters, wave velocity, wave propagation time and maximum temperature of the porous medium were determined at the lower and upper regime boundaries. The wave structure transforms as the particle diameter increases from minimum to maximum for any fixed heat transfer coefficient. At the minimum critical particle diameters, due to a significant increase in the intensity of interphase heat exchange, the temperature profiles of the phases merge and there is no sharply detached temperature peak of the gas mixture. The maximum of the heating zone thickness and minimum of the cooling zone thickness are observed at 2/3 of the particle diameter interval for any fixed heat transfer coefficient. As the upper limit (maximum diameter) is approached, the thickness of the heating zone decreases and the cooling zone increases.

1. Introduction

Published scientific works in the field of filtration gas combustion (FGC) show that FGC processes are widespread in chemical technology, power engineering, mechanical engineering, fire and explosion safety, ecology, and in everyday life [1,2].

Date: Date of Submission 1 February, 2025; Date of Acceptance 10 April, 2025, Communicated by Mamadsho Ilolov.

2000 *Mathematics Subject Classification.* Primary 35A09; Secondary 35B36.

Key words and phrases. non-adiabatic, methane-air mixture, combustion, wave velocity, porous medium, particle diameter, heat transfer coefficient, temperature profiles, numerical method, regime, boundaries, zone, heating, cooling.

In this connection, one cannot but note the fundamental experimental and theoretical studies of FGC processes [3-10], which were further continued by Belarusian [11-16] and other scientists [17-33].

Despite the fact that numerical modelling of FGC is considered to be extremely difficult, due to the large variation in the processes of gas combustion, heat transfer in porous medium, thermal interaction between the gas phase and porous medium, and heat transfer to the external medium, numerous studies have been carried out by numerical methods. Note [17], where the Runge-Kutta numerical method of the fourth order of accuracy was first applied to study the structure of the stationary FGC wave. In [18], the influence of the gas velocity and heat transfer from the surface of the frame to the external medium on the combustion parameters was analysed in a single-temperature model. Critical conditions of stationary combustion failure at the outer surface of the layer were determined. The advantages of combustion in burners with porous media were noted in [19] and a numerical and experimental study of the stabilisation of methane-air mixture combustion in inert porous media was carried out. Due to the insufficient study of the condition of flame front stabilisation inside a porous heat generator and the condition for the existence of stationary modes of gas combustion in finite-size burners, a simple model of gas combustion in a cylindrical porous burner with low thermal conductivity of the frame was proposed in [20] and a numerical study of possible stationary modes of gas combustion was carried out. Critical conditions separating different combustion modes, interesting from the practical point of view, were found. In [21] the problem of communicating flame arresters is given and the results of tests of a prototype flame arrester for flame slip and burnout are presented. It is shown that the process of burn-through of the fire barrier consists of three stages: flame entry into the porous block, propagation through it and flame exit from the porous block. It is noted that there are two parameters of the process, which can be changed within relatively wide limits, these are the average grain size of the porous medium and the level of heat loss. In [22] a numerical analysis of the burnout process of porous flame arresters was carried out and it was shown that the burnout time of channel-type porous flame arresters is determined by the time of flame entry into the porous element, while that of bulk-type flame arresters is determined by the time of propagation through it. In the work, the characteristics of industrial flame arresters and related problems are thoroughly covered. In [23], a stationary model of filtration gas combustion is proposed and numerically analysed, taking into account the conditions at the inlet to the porous body and the conditions of heat exchange with the gas phase, heat exchange with the surrounding burner, and with the heat exchanger. The parameter regions in which the gas combustion mode with a narrow reaction zone near the outer surface of the porous body is realised have been determined. In [24] a relatively complete review of experimental and theoretical works on FGC up to 2009 is presented. Numerical modelling of the processes of filtration gas combustion in inhomogeneous porous media is performed in [25]. In [26], unsteady filtration combustion of gas in an inert porous layer with consideration of the gas pressure distribution in the pores was considered, and the limits of the stationary mode of combustion inside the layer depending on the gas flow rate and interfacial heat exchange parameters were determined. It is noted that after switching off the external heating, the combustion zone is shifted downstream with the combustion front leaving the boundaries of the layer and the temperature of the frame decreases to the initial temperature. In [27], the stability of a stationary FGC wave under heat losses to the external medium was studied by the method of small perturbation theory, in the framework of a one-temperature unsteady FGC model. It is shown that the limiting heat transfer coefficient depends on the mixture inlet velocity, and parameter dependences at the boundaries of oscillatory and exponential instability are obtained, in particular, confirming the stability conditions of the condensed matter combustion front. In [28], a numerical calculation of the stationary structure of the filtration combustion wave of a hydrogen-air mixture ($65\% H_2$) in an inert heat-dissipating porous medium in the intervals of blowing velocity($0.5 - 2.5m/s$)), particle diameter ($0.5 - 9mm$), and surface heat loss coefficient ($900 - 1200W/(m^2K)$) was carried out, the FGC wave velocity, phase temperature distributions, maximum temperatures of gas and porous medium, equilibrium temperature, thickness of heating, combustion, internal relaxation and cooling zones were determined. In particular, comparisons of calculated values of the wave velocity (for different blowing velocities, compositions of hydrogen-air mixture and particle diameter equal to 1 mm) found by the ratio and numerical method are in satisfactory agreement [33].

As we can see from the above review of scientific papers, a large number of them are devoted to burners with porous media and the development of flame arresters, which are designed for localisation of combustion and are installed on storage facilities, technological devices and communications, where there is an explosive environment. In spite of the research conducted on flame arresters, there is still no design that provides flame containment for 2 or more hours.Although, the flame arrestor tests conducted on the flame containment capability for methane-air mixtures at gas flow rates of 100 and 10% of the nominal flow rate ($13.9l/s$) show that flame passage through the flame arrestor is not possible [21].Consequently, a theory or mathematical model of the FGC is needed to confirm the above tests. In this connection, in this paper, for the completeness of the FGC study, a numerical investigation of the structure of a stationary combustion wave of a methane-air mixture at the boundaries of existence of the stationary mode at downward propagation of the wave is carried out, which is not sufficiently considered in the scientific literature. Numerous temperature profiles of porous medium and gas mixture obtained by numerical Runge-Kutta method of the fourth order of accuracy are analysed. At the same time, the realisation of phase temperature profiles satisfying the boundary conditions is taken as a basis for the existence of a low-speed stationary mode of wave propagation. For dangerous velocities of methane-air mixture blowing into the porous block, the boundaries of existence of the stationary mode of wave propagation on the plane of the porous medium particle diameter and heat transfer coefficient to the external medium are determined. Here it is necessary to clarify the realisability and non-realisability of temperature profiles of porous medium and gas mixtures in the numerical solution of the problem on the structure of a stationary FGC wave. Temperature and concentration profiles are considered realisable if, when selecting the wave velocity, the calculated profiles at special points (boundary points) meet the boundary conditions (temperature and concentration gradients are equal to zero, and phase temperatures are equal to the laboratory temperature) Fig.1,2. Otherwise, the profiles are considered as not realised and the stationary regime is absent. It is assumed that in the combustion wave, the combustion zone is followed by a region of internal heat recovery and then a region of system cooling. Since a nonadiabatic combustion regime is considered, in the tail part of the wave, the temperature should decrease to the laboratory temperature [26]. The thickness of the cooling zone is defined as the difference between the coordinates of the laboratory temperature and the gas temperature at the level of the maximum temperature of the porous medium. This is due to the fact that in some phase temperature profiles a narrow region of internal heat recovery is observed, where the gas temperature sharply decreases to the maximum temperature of the porous medium. Now, the question arises why the numerical calculation of profiles is taken as a basis and is considered as a reliable result. Firstly, the numerical Runge-Kutta method of the fourth order of accuracy for solving the system of ordinary differential equations is generally recognised, secondly, the calculated temperature profiles are realistic, similar to the experimentally obtained profiles, and the selected wave velocities [17] are in agreement with theoretical and experimental results [6,16,21,33].

2. Mathematical model

An unconfined porous block is considered in comparison with the thickness of the combustion zone in which the stationary wave travels along the direction of the gas mixture flow (downwash wave). Perhaps the wave thickness in some cases exceeds the size of the porous block of the fire barrier [21], but it is not the thickness of the combustion zone, which is the smallest part of the combustion wave. In our calculations, the thickness of the combustion zone is always much smaller than the characteristic size of the porous block of the fire barrier. Therefore, we consider our studies in the framework of the steady-state FGC model acceptable. To find the travelling wave solution, the following mathematical model of the FGC is considered, consisting of the equations of heat transfer in the porous medium and gas mixture, the mass conservation equation of the mixture as a whole and the missing gas component, and the equation of state [6,16,21,26,28,32]:

$$
\begin{aligned}
&\rho_1 c_p \frac{\partial T_1}{\partial \tau} + \rho_1 c_p v_1 \frac{\partial T_1}{\partial \xi} = -\alpha_c S_c (T_1 - T_2) + \rho_1 J Q \eta_0,\\
&\rho_2 c_2 \frac{\partial T_2}{\partial \tau} = \alpha_2 \lambda_2 \frac{\partial}{\partial \xi}\left(\frac{\partial T_2}{\partial \xi}\right) + \alpha_c S_c (T_1 - T_2) + \alpha_{0,e}(T_0 - T_2),\\
&\rho_1 \frac{\partial n}{\partial \tau} + \rho_1 v_1 \frac{\partial n}{\partial \xi} = -\rho_1 J,\ J = n k_0 \exp(-E/RT),\\
&\frac{\partial \rho_1}{\partial \tau} + \frac{\partial \rho_1 v_1}{\partial \xi} = 0, \qquad \rho_1 T_1 = \rho_{10} T_{10},\\
&Nu = 0,395 Re^{0.64} Pr^{1/3},\ Re = \frac{|v_1| d_{eff} \rho_1}{\mu_1 \alpha_1},\ Pr = \frac{c_p \mu_1}{\lambda_1},
\end{aligned}
\tag{2.1}
$$

$$\alpha_c = \frac{Nu\lambda_1}{d_{eff}},\ \ d_{eff} = \frac{2\alpha_1 d_s}{3\alpha_2},\ \ S_c = \frac{6\alpha_2}{d_s},\ \ \alpha_{0,e} = \frac{2\alpha_w}{R_w}.$$

Initial and boundary conditions of the problem have the form

$$\begin{aligned}
&\tau = 0: \ T_1 = T_{10}(\xi),\ T_2 = T_{20}(\xi),\ n = 1,\\
&\xi = 0: \ T_1 = T_0,\ \ T_2 = T_0,\ \ n = 1,\\
&\xi = l: \ \frac{\partial T_1}{\partial \xi} = 0,\ \ \frac{\partial T_2}{\partial \xi} = 0,\ \ n = 0.
\end{aligned} \tag{2.2}$$

Here T_1, T_2 - temperatures of gas and porous medium respectively; n, η_0 - relative and initial mass concentration of the missing component of the mixture; v_1 - filtration rate of the gas mixture; ρ_1, ρ_2 - reduced densities of phases; c_p, c_2 - specific heat capacities of gas and porous medium; λ_2 - effective heat conductivity coefficient of porous medium;$alpha_c$ - surface heat exchange coefficient between phases; S_c - specific surface area of particles; $\alpha_{0,e}$ - heat transfer coefficient to the external medium; R_w - tube radius; Q - heat effect of reaction; E - activation energy; R - universal gas constant; k_0 - pre-exponent; Nu, Re, Pr - Nuselt numbers, Reynolds numbers, Prandtl accordingly; d_{eff} - the represented diameter of the channels; d_s - particle diameter; α_1, α_2 - volume contents of phases; μ_1 - viscosity coefficient; T_0 - initial temperature; ρ_{10} - is the reduced density of the initial mixture.

The system (1) with boundary conditions (2) is used to describe the structure of unsteady FGC waves. As we can see, this model neglects diffusion and heat conduction processes in the gas mixture due to their relative insignificance in comparison with the thermal conductivity of the porous medium and the intensity of heat exchanges (internal and external). Here, the wave refers to the profiles of temperatures (gas, porous medium) and concentration of the missing component of the mixture, which depend on time and coordinates. Note that in combustion theory, to study the structure of stationary combustion waves, one moves to a mobile coordinate system by means of a linear transformation of the coordinate system. It is assumed that all the unknown functions included in the system do not depend on time, and, as a consequence, the time derivatives of these functions are considered to be equal to zero. But, the obtained system of differential equations contains an additional unknown constant of the wave velocity - U, which complicates the solution of the problem. In spite of this, in the present work, the transition to the mobile coordinate system ($x = \xi - U\tau, t = \tau$) is also carried out, and the system (2.1) has the form

$$\begin{aligned}
&\rho_1 c_1 (v_1 - U)\frac{dT_1}{dx} = -\alpha_c S_c (T_1 - T_2) + \rho_1 Q \eta_0 J,\\
&-\rho_2 c_2 U \frac{dT_2}{dx} = \alpha_2 \lambda_2 \frac{d^2 T_2}{dx^2} + \alpha_c S_c (T_1 - T_2) + \alpha_{0,e}(T_0 - T_2),\\
&\rho_1 (v_1 - U)\frac{dn}{dx} = -\rho_1 J,\ \ J = n k_0 \exp(-E/RT_1),\\
&\rho_1 (v_1 - U) = \rho_{10}(v_{10} - U),\ \ \rho_1 T_1 = \rho_{10} T_0.
\end{aligned} \tag{2.3}$$

In this case, the boundary conditions are set at infinity

$$\begin{aligned} &x \to -\infty: \ T_1 = T_0, \ \ T_2 = T_0, \ \ n = 1, \\ &x \to +\infty: \ \frac{dT_1}{dx} = 0, \ \frac{dT_2}{dx} = 0, \ \ n = 0. \end{aligned} \tag{2.4}$$

For numerical solution of the problem, the system (2.3) and boundary conditions (2.4) are appropriately decimated. The stationary velocity is chosen in such a way that the solution of the unmeasured system (2.3) leaves one special point ($T_1 = T_0, \ T_2 = T_0, \ n = 1$) and enters another ($\frac{dT_1}{dx} = 0, \ \frac{dT_2}{dx} = 0, \ n = 0$). To exit the region where the chemical reaction rate is negligible, the analytical solution of system (2.3) is used (in the absence of the heat release term due to the chemical reaction).

3. Results and their discussion

Note that all results given in the present work refer to 8.5% methane in the total methane-air mixture and do not essentially differ from the results for the stoichimetric mixture ($9.5\%CH_4$). The upper and lower limits of existence of the low-velocity stationary mode of wave propagation in filtration combustion of methane-air mixture are defined on the plane of heat transfer coefficient and particle diameter of porous medium. That is, at a fixed heat transfer coefficient there is an interval of values of the porous medium particle diameter (from minimum to maximum) at which stationary phase temperature profiles are numerically realised. Fig.1,2 show variants of realisation of phase temperature profiles at the lower and upper boundaries of existence of low-speed stationary mode of filtration wave propagation of methane-air mixture combustion respectively. Similar profiles were obtained in the form of functional dependence of phase temperatures on time and coordinates during the theoretical study of the problem within the framework of the equivalent unsteady FGC model in the presence of heat losses [32,34]. The one-temperature regime (Fig.1) is realised at the lower regime boundary, at relatively small particle diameters of the porous medium. The step of dimensionless grid in all calculations is equal to $2 \cdot 10^6$, on the graphs of temperature values is printed after 1000 steps. The thickness of the porous block equal to 0.1 m is taken as a characteristic size. Calculations were carried out at the following values of physicochemical parameters of porous medium and methane-air mixture [19,20]

$$\begin{aligned} &\rho_1^0 = 1.142kg/m^3, \ \rho_2^0 = 3900kg/m^3, \ c_p = 1000J/(kgK), \ c_2 = 800J/(kgK), \\ &\lambda_1 = 0.1W/(mK), \ \lambda_2 = 0.5W/(mK), \ T_b = 2320K, \ T_0 = 300K, \ \eta_0 = 0.085, \\ &\alpha_1 = 0.45, \ \alpha_2 = 0.55, \ k_0 = 10^11, \ E = 226000J/mol. \end{aligned}$$

A tube with a diameter of 180 mm ($R_w = 0.09m$) was considered, as in [19,20]. The heat loss per unit of the external surface of the flame arrestor α_w was assumed to be equal to $\{200, 400, ...1600W/(m^2K)\}$, respectively, the volumetric heat loss $\alpha_{0,e}$ was calculated according to the above formula. At $\alpha_w = 200W/(m^2K)$, the volume heat loss was equal to $\alpha_{0,e} = 4444, 44W/(m^3K)$. Since only the volumetric heat transfer coefficient ($\alpha_{0,e}$) was used in the numerical calculation, the results of the calculations will be true for variationsα_w and R_w at constant value of the volumetric heat transfer coefficient. For example, with the volumetric heat transfer coefficient $\alpha_{0,e} = 4444,44W/(m^3K)$, we can choose the surface heat transfer coefficient equal to $\alpha_w = 50W/(m^2K)$,then the radius of the tube will be equal to $R_w = 0.0225m$ or with$\alpha_{0,e} = 35555,55W/(m^3K)$ and $R_w = 0.04m$, the surface heat transfer coefficient will be equal to $\alpha_w = 711,11W/(m^2K)$.

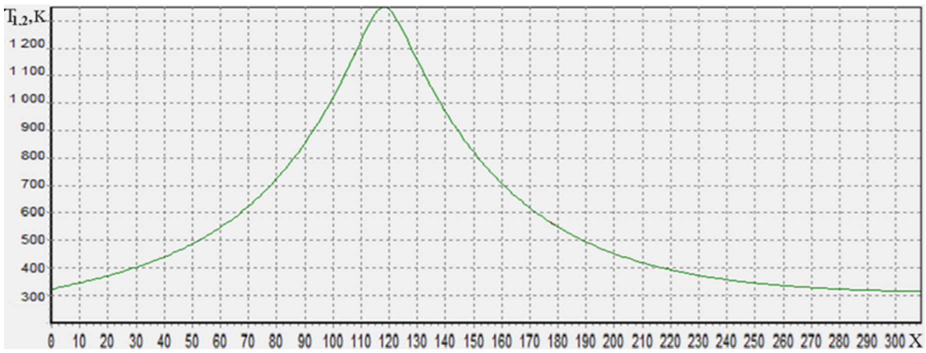

Figure 1.Temperature profiles of porous medium and gas at the lower boundary of the regime: $\alpha_{0,e} = 4444,44W/(m^3K)$,
$d_s = 0.01mm, U = 0.00015915m/s, v_{10} = 0.535m/c$.

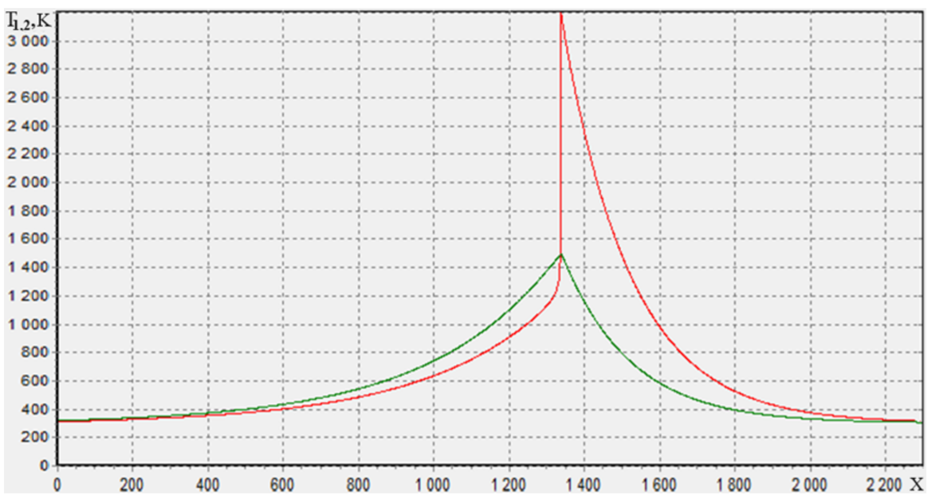

Figure 2.Temperature profiles of porous medium and gas at the upper boundary of the regime: $\alpha_{0,e} = 4444,44W/(m^3K)$,
$d_s = 22mm, U = 0.00015915m/s, v_{10} = 0.535m/c$.

As can be seen from Fig.1,2 the structure of the wave transforms essentially at change of diameter of particles of porous medium from minimum to maximum. In this case, the coordinates of the maximum temperature and the thickness of the heating zone, at 2/3 of the particle diameter interval (at any heat transfer coefficient of the considered ones), increase to some value, and then, when approaching the upper limit (maximum diameter), decrease, that is, it has a maximum in the particle diameter intervals. Thicknesses of heating and cooling zones at critical particle diameters decrease as the intensity of external heat exchange increases.

Table 1 shows the maximum and minimum diameters of porous medium particles depending on the heat transfer coefficient to the external medium at fixed mixture injection velocities, within which there is a low-speed stationary mode of wave propagation. Note that the maximum particle diameters decrease as the heat transfer coefficient increases (decreasing the minimum tube diameter), while the minimum diameters increase. So, at some heat transfer coefficient they will be equal and further, the solution of the problem does not exist, for example, in the case of blowing velocity equal to 0.214 m/s (Tab.1). At further reduction of the inlet velocity, the point of intersection of the maximum and minimum diameters of the porous medium particles moves towards the reduction of the heat transfer coefficient, hence, there is a certain minimum heat transfer coefficient to the external medium at which there is no stationary mode. Here, at the lower limit, the fact that the decrease in the intensity of internal heat transfer (increase in the minimum diameter of porous medium particles) is accompanied by an increase in the external heat transfer [6] is revealed. As a result, we draw the following conclusions from Tab.1: for a fixed velocity of mixture injection there is a maximum heat transfer coefficient to the external medium (minimum tube diameter) above which there is no low-speed stationary mode, and below it 'there are two branches of the solution merging and disappearing' [6]. In addition, there are the minimum mixture inlet velocity and the minimum heat transfer coefficient (maximum tube diameter) below which there is no solution to the problem, which confirms the statement of [20] that the propagation of the combustion wave is possible in a limited range of mixture inlet velocities.

Table 1.Intervals of porous medium particle diameters, at which there is a stationary mode of wave propagation (d_s, mm)

$\alpha_{0,e}$, W/(m^{3}K)	4444,44	8888,89	13333,33	17777,78	22222,22	26666,67	31111,11	35555,55
v_{10} = 0,214 m/s	0,2÷13,0	0,4÷6,6	0,4÷4,0	0,4÷2,6	0,4÷1,8	0,4÷1,0	не сущ.	не сущ.
v_{10} = 0,24 m/s	0,05÷14,0	0,1÷7,4	0,2÷4,6	0,2÷3,2	0,2÷2,2	0,4÷1,6	0,4÷1,2	0,4÷0,6
v_{10} = 0,535 m/s	0,01÷22,0	0,01÷12,0	0,01÷8,5	0,01÷6,5	0,01÷5,5	0,01÷4,5	0,01÷4,0	0,01÷3,5

Table 2 shows the effective pore diameters at the upper boundary of the steady-state regime at different mixture injection rates and heat transfer coefficients. As can be seen from the table, at the boundary of the regime with increasing heat transfer coefficient the pore diameters decrease, but at fixed heat transfer coefficient there is an increase in pore diameter with increasing methane-air mixture injection rate.

Table 2. Effective pore diameters at the upper pore diameters at the upper boundary of the steady-state regime, mm

$\alpha_{0,e}$, W/(m^{3}K)	4444,44	8888,89	13333,33	17777,78	22222,22	26666,67	31111,11	35555,56
$v_{10} = 0{,}214$ m/s	7,09	3,60	2,18	1,42	0,98	0,60		
$v_{10} = 0{,}24$ m/s	7,64	4,04	2,51	1,80	1,31	0,93	0,65	0,33
$v_{10} = 0{,}535$ m/s	12,00	6,55	4,64	3,55	3,67	3,00	2,67	2,33

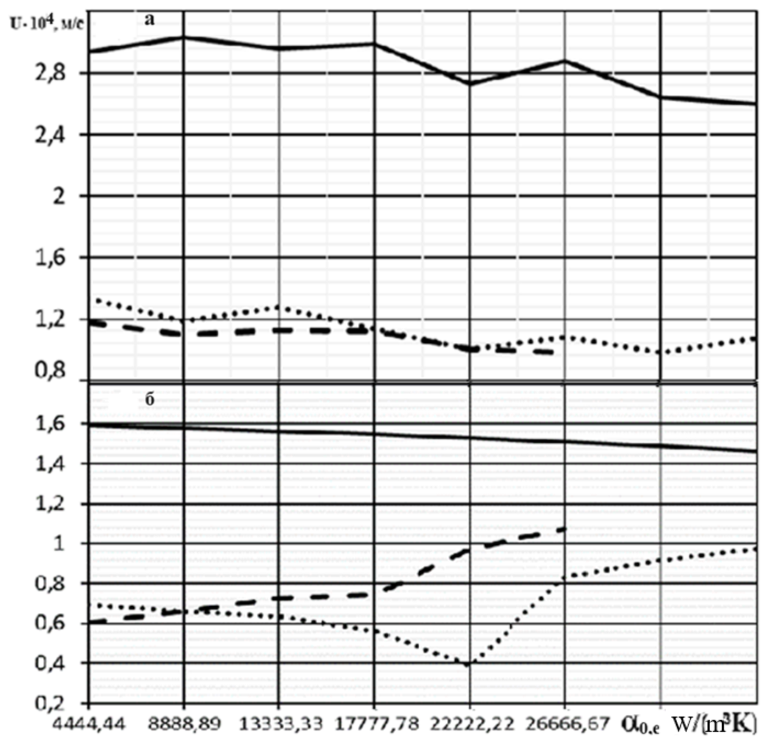

Figure 3. Dependences of the stationary wave velocity at the upper (a) and lower (b) regime boundaries: curves correspond to the mixture inlet velocities, solid - 0.535 m/s, dashed - 0.214 m/s, with dots - 0.24 m/s.

Fig.3 shows the dependences of the stationary wave velocity on the heat transfer coefficient at the upper (a) and lower (b) boundaries of the stationary mode existence. It should be noted that at the upper boundary of the regime (Fig.3,a), a slight decrease of the stationary wave velocity is observed for all considered mixture blowing velocities, and the values of the wave velocity for relatively high blowing velocity ($0.535 m/s$) of the considered ones increase approximately 2.5 times in comparison with low blowing velocities. At the lower boundary of the stationary regime (Fig.3, b), the wave velocity decreases slightly as the heat transfer coefficient increases only for the blowing velocity of 0.535 m/s, and for relatively low blowing velocities, its increase is observed. The analysis of the wave propagation velocity shows that a significant decrease in the critical particle diameter at the upper boundary of the mode does not lead to a significant reduction of the wave velocity and, as a consequence, does not increase the burnout time of the flame arrestor.

To determine the burnout time of a fire barrier, it is necessary to know the time of wave formation and propagation through the porous block [19], and for a fire barrier with a bulk porous block - the time of wave propagation [20]. The latter, confirmed within the framework of the equivalent unsteady FGC model [30], that the wave formation time at the entrance of the porous block is negligible. The wave propagation time is determined by the thickness of the porous block (10 cm) and the steady-state wave propagation velocity, $t = 0.1/U$. Below in Table 3 are the burn-through times of the fire barrier in minutes at the lower and upper limits of steady-state existence, respectively. From Table 3, it can be seen that the burn-in time at the upper boundary increases slightly with increasing heat transfer coefficient (as the wave velocity decreases), while it decreases at the lower boundary for mixture inlet velocities of 0.214 m/s and 0.24 m/s. In addition, it is observed that the burn-up time decreases by about a factor of two for relatively small values of the heat transfer coefficient as the particle diameter increases from the minimum to the maximum.

Table 3. Flame arrestor burn-through time at the lower and upper limits, respectively, min.

$\alpha_{0,e}$, W/(m^{3}K)	4444,44	8888,89	13333,33	17777,78	22222,22	26666,67	31111,11	35555,56
$\upsilon_{10} = 0{,}214$ m/s	27,41	25,26	22,90	22,38	17,10	15,54		
$\upsilon_{10} = 0{,}24$ m/s	24,07	25,28	26,34	29,78	42,86	20,07	18,20	17,11
$\upsilon_{10} = 0{,}535$ m/s	10,47	10,56	10,66	10,78	10,90	11,04	11,20	11,38
$\boldsymbol{\upsilon_{10} = 0{,}214}$ m/s	14,14827	15,2207	14,80166	14,88095	16,66667	17,0068		
$\boldsymbol{\upsilon_{10} = 0{,}24}$ m/s	12,50313	14,0647	13,0719	14,74926	16,66667	15,4321	17,0068	15,48947
$\boldsymbol{\upsilon_{10} = 0{,}535}$ m/s	5,668934	5,50055	5,630631	5,574136	6,105006	5,787037	6,313131	6,410256

To clarify the issue of melting of porous block material during combustion, it is very important to know how much the porous medium heats up within the limits of existence of the stationary regime. In this connection, Fig. 4 shows the dependences of the maximum temperature of the porous medium on the heat transfer coefficient at the upper (a) and lower (b) boundaries of the steady-state regime for the considered velocities of the mixture blowing. From Fig. 4 we notice that at the upper boundary, the porous medium temperature increases in the interval from 1400K to 1630K as the heat transfer coefficient increases, and at the lower boundary from 1350K to 1550K.

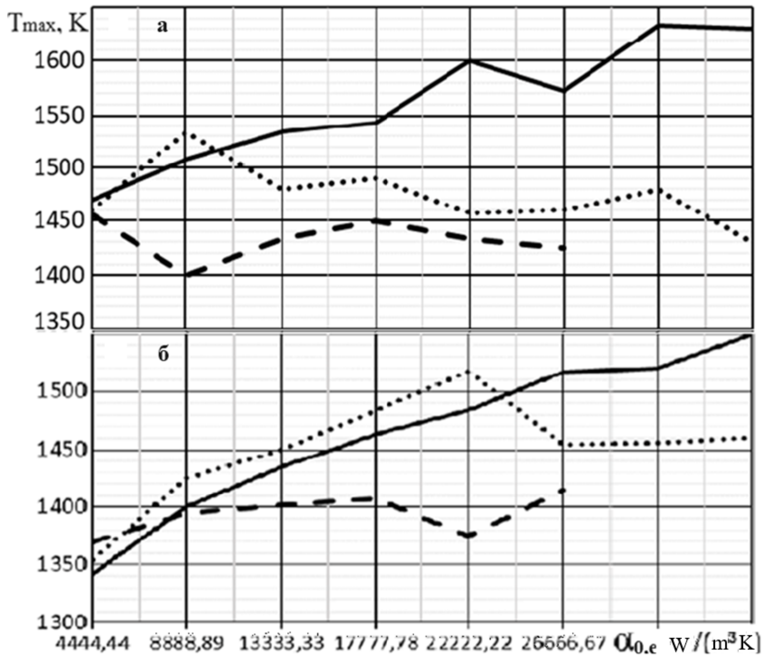

Figure 4. Maximum temperatures of the porous medium at the upper (a) and lower boundaries (b) of the stationary regime existence: curves correspond to the mixture blow-in velocities, solid - 0.535 m/s, dashed - 0.214 m/s, with dots - 0.24 m/s..

Thus, if we proceed from the fact that 'under certain conditions the combustion wave is not formed in the porous block at all and such a fire barrier will not burn out' [20], then the condition of not realising the phase temperature profiles in our study is the condition of not burning out the fire barrier [20], then the condition of not realising the phase temperature profiles in our study is the condition of not burning through the fire barrier. The existence of critical diameters of porous medium particles when varying different parameters is convenient from a practical point of view, as it expands the possibilities of controlling the combustion process in order to select the most optimal solution.

4. Conclusions

Numerical modelling of profiles temperature of gas and porous medium at non-adiabatic filtration combustion of methane-air mixture allowed to establish:

- limits of existence of a low-speed stationary mode of wave propagation on the plane of the porous medium particle diameter and heat transfer coefficient to the external medium;
- absence of the stationary mode at relatively high heat transfer coefficients and relatively low velocities of mixture injection;
- limits of variation of the maximum temperature of the porous medium at the boundaries of the stationary regime existence;
- non-significant change of the wave propagation velocity at the regime boundaries;
- confirmation of regularities of wave propagation at counterflow.

References

[1] Mosbauer, S., Pickenacker, O., Pickenacker, K., Trimis, D. *Application of the porous burner technology in energy- and heat engineering*, Proc. of V Int. Conf. on Technologies and Combustion for a Clean Environment (clean Air V). - Lisbone (Portugal), 12-15 July, 1, 20.2, 519-523 (1999)

[2] Oliveira, A.A., Kaviany, M. *Nonequilibrium in the transport of heat and reactants in combustion in porous media*, Progress in energy and combustion science, 27, 3, 523-545 (2001)

[3] Korzhavin, A.A., Bunev, V.A., Abdullin, R.Kh., Babkin, V.S. *Flame zone in gas combustion in an inert porous medium*, Combustion, Explosion and Shock Waves, 18, 628-631 (1982)

[4] Babkin, V.S., Drobishevich, V.I., Laevskiy, Y.M., Potytnyakov, S.I. *On the mechanism of combustion wave propagation in porous medium during gas filtration*, Reports of the Academy of Sciences of the USSR, 265, 5, 1157-1161 (1982)

[5] Babkin, V.S., Drobishevich, V.I., Laevskiy, Y.M., Potytnyakov, S.I. *Filtration combustion of gases*, Combustion, Explosion and Shock Waves, 19, 147-155 (1983)

[6] Potytnyakov, S.I., Laevskiy, Y.M., Babkin, V.S. *Effect of heat losses on propagation of stationary waves in filtration combustion of gases*, Combustion, Explosion and Shock Waves, 20, 15-22 (1984)

[7] Potytnyakov, S.I., Babkin, V.S., Laevskiy, Y.M., Drobishevich, V.I. *Thermal structure of an in situ gas combustion wave*, Combustion, Explosion and Shock Waves, 21, 146-151 (1985)

[8] Lyamin, G.A., Pinaev A.V. *Combustion regimes for gases in an inert porous material*, Combustion, Explosion and Shock Waves, 22, 553-558 (1986)

[9] Babkin, V.S., Korzhavin, A.A., Bunev, V.A. *Propagation of Premixed Gaseous Explosion Flames in Porous Media* Comb. Flame, 87, 182-190 (1991).

[10] Babkin, V.S. *Filtrational combustion of gases. Present state of affair and prospect*, Pure and Appl. Chem., 65, 2, 335-344 (1993).

[11] Rabinovich, O. S. *Modeling of premixed gas combustion in porous media, composed of coarse-sized particles: 1-D description with discrete solid phase*, 26 Intern. Symp. on Combustion. Pittsburgh:The Combustion Inst, 3383-3389 (1996).

[12] Fateev, G.A, Rabinovich, O.S. *Interaction of Superadiabatic Combustion and Heat Conversion Waves in a Porous Medium with Incorporated Metal Hydride Elements*, 27th Symp. (Int.) on Combustion. Pittsburgh,PA. The Combustion Institute, 2451-2458 (1998).

[13] Shabunya, S.I. and Martynenko, V.V. *Two-Dimensional Modeling of Filtration Combustion in Porous Charges in a One-Temperature Approximation*, Inzhenerno-fizicheskii Zhurnal, 71, 6, 963-970 (1998)

[14] Dobrego, K. V., Zhdanok, S.A., Khanevich, E.I. *Analytical and Experimental Investigation of the Transition from Low-velocity to High-velocity Regime of Filtration Combustion*, Exper. Thermal and Fluid Sci., 21, 9-16 (2000)

[15] Dobrego, K.V., Zhdanok, S.A., Zaruba, A.I. *Experimental and Analytical Investigation of the Gas Filtration Combustion Inclination Instability*, Int. J. Heat and Mass Transfer, 44, 2127-2136 (2001).

[16] Dobrego, K.V., Zhdanok, S.A. *Physics of filtration combustion of gases*, Mn.: Int. of Heat and Mass Exchange named after A.V. Lykov NASB, 2002

[17] Vainshtein, P.B., Kabilov,M.M. *To the theory of filtration combustion of gases in porous media*, News of the National Academy of Sciences of Tajikistan. Department of physical, mathematical, chemical, geological and technical sciences, 3, 55-59 (1992)

[18] Burkina, R.S. *Filtration combustion of a gas in a semiinfinite porous medium* Combustion, Explosion and Shock Waves, 36, 417 - 427 (2000)

[19] Brenner, G., Pickenacker, K., Pickenacker, O., Trimis, D., Wawrzinek, K., Weber, T. *Numerical and experimental investigation of matrix-stabilized metan/air combustion in porous inert media*, Combustion and Flame, 123, 201-203 (2000)

[20] Knyazeva, A.G., Nemytov, V. P. *Numerical study of gas combustion modes in a porous cylindrical burner with low thermal conductivity of the frame*, Proceedings of Tomsk Polytechnic University, 309, 3, 126-130 (2006)

[21] Kakutkina, N.A., Korzhavin, I.G., Namyatov, D.A., Rychkov, A.A. *Flame propagation through the header of an in-line flame arrester*, Combustion, Explosion and Shock Waves, 43, 391-404 (2007)

[22] Kakutkina, N.A., Korzhavin, I.G., Rychkov, A.A. *Burning-through of porous flame arresters with a channel flame-arrester element*, Combustion, Explosion and Shock Waves, 45, 3, 266 - 273 (2009)

[23] Chumakov, Yu. A., Knyazeva, A. G. *Regimes of gas combustion in a porous body of a cylindrical heat generator*, Combustion, Explosion and Shock Waves, 45, 14-24 (2009)

[24] Abdul Mujeebu, M., Abdullah, M.Z., Abu Bakar, M.Z., Mohamad, A.A., N.Muhad, R. M., Abdullah, M.K. *Combustion in porous media its applications - A comprehensive survey*, J. Environment Management, 90, 2287-2312 (2009).

[25] Laevsky, Yu.M., Yausheva, L.V. *Simulation of the filtrating gas combustion processes in non-homogeneous porous media*, Siberian J. Num. Math., 12, 171-187 (2009).

[26] Prokof'ev, V. G., Kirdyashkin, A. I., Smolyakov, V. K. *Unsteady combustion of gases in an inert porous layer*, Combustion, Explosion and Shock Waves, 46, 641-646 (2010)

[27] Kabilov, M.M. *Instability of the front of filtration combustion of gases in the nonadiabatic regime*, Combustion, Explosion and Shock Waves, 48, 136-143 (2012)

[28] Kabilov, M.M., Khalimov, I.Kh. *Numerical investigation of a stationary wave structure of filtration combustion of gases in the case of heat loss*, Reports of the National Academy of Sciencesof Tajikistan, 56, 4, 297-304 (2013)

[29] Kandryukova, T.A., Laevsky, Y.M. *On the numerical modelling on multicore computing systems*, Siberian Journal of Industrial Mathematics, 17, 55-64 (2014)

[30] Nosova, T.A. *Computational models of filtration gas combustion in the low velocity regime*, Diss... kand. physico-mathem. sciences: 05.13.18. - Ins. of computational mat. and mat. geophysics SB RAS, Novosibirsk, 2018

[31] Khalimov, I.I. *Super- and subadiabatic modes of filtration combustion of gases in the equivalent mathematical model*, Dis... kand. of physico-mathem. sciences: 05.13.18. - Taj. national. university, Dushanbe, 2021

[32] Kabilov, M.M., Shermatova, Z.B. *Equivalent mathematical model of filtration combustion of gases in the presence of heat losses*, Reports of the National Academy of Sciencesof Tajikistan, 66, 187-195 (2023)

[33] Kabilov, M.M., Shermatova,Z.B., Sadriddinov, P.B. *Maximum temperatures of gas, porous medium and velocity of stationary wave of filtration combustion of hydrogen-air mixture in the presence of heat losses*, Chelyabinsk Physical and Mathematical Journal, 9, 240-246 (2024)

[34] Kabilov, M.M. And Gulboev B.J. Similarity of temperature and concentration fields in filtration combustion of gases. Journal of Applied Data Analysis and Modern Stochastic Modelling Vol. 1 No. 1 (June, 2024). pp. 29-38 (https://jadamsm.yolasite.com/resources/3.%20Kabilov%20M.pdf)

Kabilov M.M.: Russian-Tajik (Slavic) University
Email address: maruf1960@mail.ru

Khalimov I.I.: Russian-Tajik (Slavic) University
Email address: halimov1963@mail.ru

Shermatova Z.B.: Russian-Tajik (Slavic) University
Email address: shermatova333@bk.ru