Experimental and Numerical Study of Premixed Flame Penetration in a Set of Microchannels

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1 Introduction

Effective heat recirculation mechanisms inherent to combustion processes in porous media result in several features relative to a free-burning flame. These features include higher burning velocities, superadiabatic temperature in the reaction zone [1], extension of the flammability limits [2], low emission of pollutants [3] and the ability to burn fuels with a low energy content. These features have found practical use in a number of applications [4] which in turn stimulated further fundamental investigations of filtrational gas combustion in inert porous media and microchannels systems [5]. Whereas a large number of theoretical and numerical studies are dedicated to the combustion processes in the interior of porous media, the flame behavior in the vicinity of porous media / open space interface is less investigated. Particularly, many aspects concerning flame dynamics in the course of combustion wave penetration in porous media were not considered in details. At the same time, flame stabilization near the porous body boundary is typical for many practical burners. Fundamental investigations of flame penetration inside the porous media meet some difficulties associated with opacity of most materials that prevents visual observations and uncontrolled irregularity on the pore scales which hampers deducing of general regularities. Some similarity between filtrational gas combustion and flame propagating in the narrow channels [6] suggests that investigations of idealized system consists of the set of microchannels may provide relevant knowledge on flame behavior near the boundaries of porous media. In such microchannels system it is possible to exclude probabilistic factors associated with porous media irregularity and investigate only effects of heat and mass transfer on flame behavior.

This paper presents the results of experimental and numerical study of flame penetration in the set of planar quartz ducts with non-uniform channel sizes. Such configuration allow us to observe flame dynamics and control spatial distribution of channels sizes by variation of the gaps between the quartz plates forming ducts. The regions of existence of different combustion regimes in equivalence ratio / mixture flow rate plane were obtained for the channels of different transverse sizes. Besides the fundamental knowledges on flame behavior in the vicinity of interface between microchannels array and free space, presented results can qualitatively describe the main features of combustion wave penetration inside the porous media.

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2 Experimental setup

Photograph of the multi-channel burner is shown in Fig. 1. The quartz plates of 6 cm width, 12 cm height and 0.1 cm thickness form the channels walls. The gap between the plates can be varied from 0.1 cm to 1 cm. The total number of the channels in the system depends on their transverse size and ranges from 1 to 20. Methane-air mixture is supplied to the channels through the rectangular slot which size fits the total size of the multi-channel system. Three-layer fine steel mesh is embedded to the slot in order to provide near flat flow velocity profile. The control system consists of a PC, mass flow controllers and AD/DA converters. The mixture is ignited at the outlet of the channels by pilot flame which is removed immediately after flame initiation. The flame behavior is recorded with two photo cameras which are mounted perpendicular and parallel to the quartz plates forming the channels.

Three different configurations of the multi-channel burner differing in inner size of the channels were studied experimentally. The first and second configurations consist of seven equally sized channels of transverse distances 0.3 and 0.1 cm respectively. Below we will refer these configurations as I and II. In the third configuration which will be denoted as III, the channels of inner size 0.1 and 0.3 cm alternate. In this case, the transverse size of outside channels is 0.3 cm and the total number of channels is 7. Flame behavior was investigated in the range of equivalence ratios from 0.7 to 1.3. Notice that for stoichiometric methane-air mixture quenching distance is about 0.22 cm and it is about 0.3 cm for equivalence ratios 0.8 and 1.2.

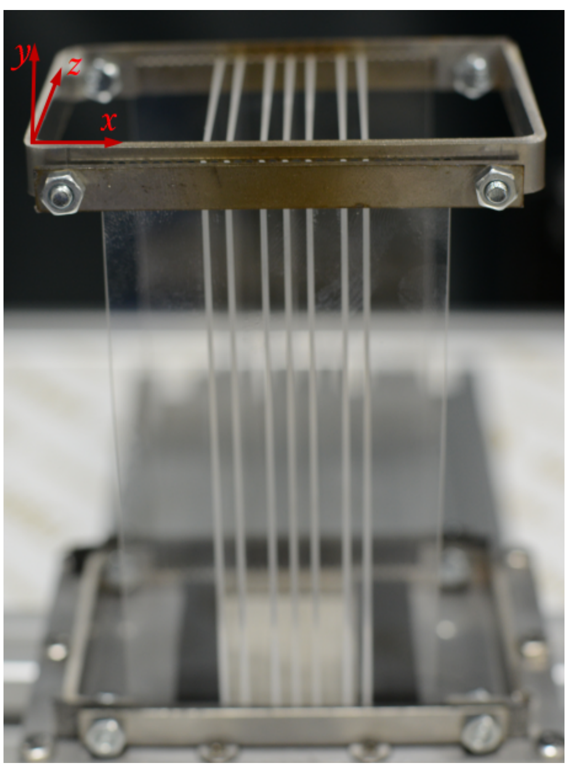

Fig.1. Photograph of the multi-channel burner.

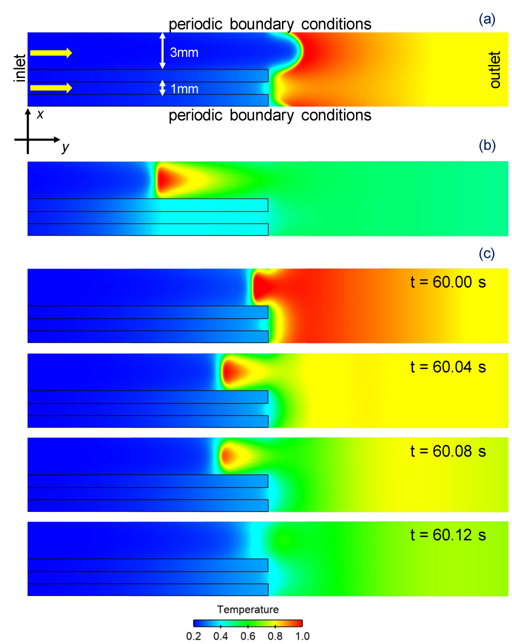

Fig.2. Temperature distributions for different combustion modes in configuration III calculated for $Q = 285$ cm^3/s (a), $Q = 125$ cm^3/s (b) and $Q = 95$ cm^3/s (c).

3 Mathematical model

Premixed flame penetration in the multi-channel burner was studied numerically in the frame of thermal-diffusion model with prescribed time-independent velocity flow field. The set of unsteady two-dimensional equations for gas temperature, temperature of the walls and fuel concentration can be written in the following non-dimensional form:

$$\partial T/\partial t + (\mathbf{V}\nabla)T = \Delta T + (1-\sigma)W - h_r(T^4 - \sigma^4) \quad (1)$$

$$\partial \Theta/\partial t = \kappa \Delta \Theta \quad (2)$$

$$\partial C/\partial t + (\mathbf{V}\nabla)C = Le^{-1}\Delta C - W \quad (3)$$

Where $W = ((1-\sigma)N)^2/(2Le)C\exp(N(1-1/T))$ is the chemical reaction rate and $\mathbf{V} = (V_x, V_y)$ is the dimensionless time-independent velocity vector pre-calculated for the non-reactive mixture in examined channels configuration; T and Θ is the non-dimensional gas and wall temperature in units of T_b, the adiabatic temperature of combustion products; C is the non-dimensional concentration of the deficient reactant in units of C_0, its value in the fresh mixture; x, y is non-dimensional spatial coordinates in units of flame thermal thickness $l_{th} = D_{th}/U_b$, where D_{th} is the mixture thermal diffusivity and U_b is the laminar burning velocity; t is non-dimensional time in units $t_{th} = D_{th}/U_b^2$; $\sigma = T_0/T_b$ where T_0 is the fresh mixture temperature; Le is the Lewis number; $N = T_a/T_b$ is the scaled activation energy and T_a is the activation temperature; h_r is the non-dimensional radiative heat loss intensity; $\kappa = D_s/D_{th}$, where D_s is thermal diffusivity of the channels wall.

Equations (1)-(3) are supplemented by boundary conditions at the inlet ($T = \Theta = \sigma$, $C = 1$) and outlet ($\partial T/\partial y = \partial \Theta/\partial y = \partial C/\partial y = 0$). At the interface between gas and solid phase the Newton's heat exchange boundary conditions are applied. Radiation heat losses are considered only from the outlet faces of the channels walls. Computation domain includes two channels of same or different transverse sizes as shown in Fig. 2. Herewith, periodic boundary conditions in x direction are used.

Equations (1)-(3) with boundary conditions were solved numerically by finite-difference explicit scheme. Velocity field was pre-calculated by SIMPLE algorithm for non-reactive flow. Problem parameters were chosen as $N = 7.5$, $\sigma = 0.15$, $Le = 0.9$ that roughly corresponds to the methane-air mixture with $\phi = 0.8$. Investigations of Lewis number effect, effects of boundary conditions and others will be matter of further study. Here we restrict ourself by numerical simulations with parameters roughly correspond to experimental conditions. Convergence of the numerical scheme was checked by the simulations on a set of gradually refining grids.

4 Results and discussion

Experiments show that depending on channels configuration, equivalence ratio and mixture flow rate the different flame behaviors are observed. Regime diagram in Fig. 3a demonstrates the regions of existence of different combustion regimes in equivalence ratio (ϕ) / mixture flow rate (Q) plane obtained for the examined configurations of the multi-channel burner. At high flow rates the flames are stabilized at the channels outlets and their shape is almost independent on z-coordinate (see Fig. 1). In xy-plane the flames have concave shape with the tip located at the central axis of the corresponding channel and directed in the flow direction. The bottom parts of the flames are attached to the top rims of the plates forming the channel. Such flame topology is typical for the burner stabilized flames. In Fig. 3a this combustion regime

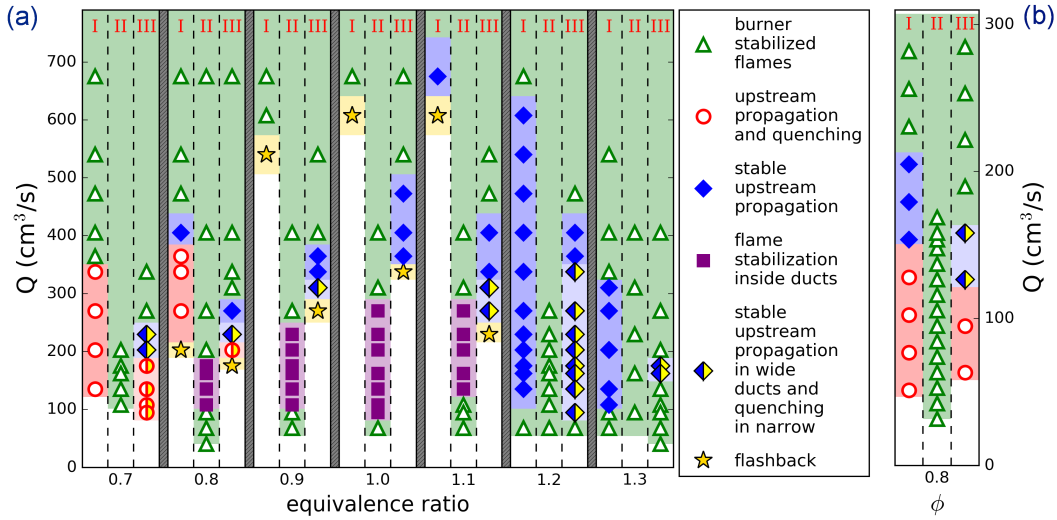

Fig.3. Experimental (a) and numerical (b) regime diagrams.

is marked by green triangles. With the decrease of mixture flow rate the flames height is also decreased. For relatively wide channels of 0.3 cm size (configuration I) the range of inlet velocities for which the flames can penetrate inside the multi-channel burner exists. Herewith, for lean mixtures with $\phi = 0.7$ the flames are quenched at a certain depth from the top of the burner (red circles in Fig. 3a), while for $\phi = 0.8, 1.1 - 1.3$ after the penetration stage the upstream flame propagation is observed (blue diamonds in Fig. 3a). At relatively small flow rates the upstream flame propagation becomes unstable. The instability manifests itself in flame repetitive extinction and re-ignition. The flame propagation in this case is accompanied with noticeable sound. Such flame behavior is associated with the temperature gradient in the channels walls and have the same nature as FREI (flame repetitive extinction and ignition) regime previously observed in the experiments on combustion in externally heated narrow tube [7]. Despite of flames pulsations the average position of combustion wave shifts upstream with almost constant velocity. It was experimentally found that for upstream propagating combustion waves the average flame speed ranges from 0.05 to 0.3 mm/s and its dependence on inlet mixture velocity shows U-shape form. Such behavior is typical for the low velocity regime of filtrational combustion waves [1, 6]. For near-stoichiometric methane-air flames ($\phi = 0.9, 1.0$) in channels configuration I the only two combustion regimes are observed, namely burner stabilized flames at high mixture flow rates and flashback (yellow stars in Fig. 3a) at relatively low inlet velocities.

Regime diagrams obtained for the set of equally sized narrow channels of transverse size 0.1 cm (configuration II) significantly differ from those for configuration I. For the mixtures far from stoichiometric ($\phi = 0.7, 1.2, 1.3$) the flame penetration inside the channels becomes impossible and only burner stabilized flames are observed over whole range of mass flow rates. It can be assumed that it is due to the increasing of surface-to-volume ratio resulting in intensification of external heat losses. In the range of equivalence ratios from 0.8 to 1.1 and moderate mixture flow rates the flames settle inside the channels at certain distances from their outlet. Although the FREI phenomenon is observed under some conditions, the average positions of flames inside the channels remains constant. In regime diagram (Fig. 3a) this combustion mode is marked by rectangles. Typical front and side views of the multi-channels burner operating in this regime are shown in Fig. 4. In yz-plane (see Fig. 1) flames in the channels have shape of cup whose edges are attached to the top rim of the channels walls. The distance between the channels outlet and the deepest point of the flame is maximal in the central channel and minimal in the side channels. Such flames shape is a result of heat

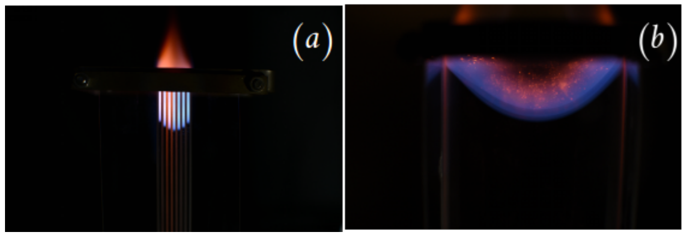

Fig.4. Front and side views of the flames stabilized inside the channels at ϕ=1, Q=202.5 cm^3/s.

losses to the ambient. Experiments show that flame curvature depends on equivalence ratio and mass flow rate. The higher inlet mixture velocity, the deeper flames submergence in the channels. This is quite in line with basic combustion theory concepts asserting direct dependency of burning velocity on flame surface area. Possibility of flame stabilization in the wide range of problem parameters such as inlet velocity and equivalence ratio is associated with effects of external heat losses and variation of flames surface area.

In contrast to configuration II, for configuration III which consists of alternating wide and narrow channels the stable upstream flames propagation becomes possible. At relatively high inlet velocities the combustion waves propagates in both wide and narrow channels (blue diamonds in Fig. 3a), while for moderate mixture flow rates and $\phi = 0.7 - 0.9$ the flames in narrow channels are quenched and reaction waves are observed in wide channels only (half-shaded diamonds in Fig. 3a). It should be noted, that at high flow rates the flame propagation in wide channels is almost uniform while in narrow ducts repetitive flame extinction and re-ignition accompanied by popping sound takes place. Experimental results suggest that heat exchange between wide and narrow channels determines flame dynamics in these combustion regimes. At high flow rates the flame propagation velocity is lower that results in more effective heating of the narrow channels by the flames in neighboring wide channels and provides the possibility of flame re-ignition and propagation in narrow ducts. At low mixture flow rates or equivalence ratios far from stoichiometric such heating becomes insufficient to maintain combustion in narrow channels. Interestingly, that the range of inlet velocity for which the upstream flames propagation is observed is much wider for the fuel rich mixtures. It may be due to supporting influence of afterburning in diffusion flame which is stabilized at the burner outlet.

Experimental observations of flame dynamics in the course of combustion wave penetration in the multi-channels burner show that flames enter in the narrow channels first. After some transition period necessary to heat channel walls the flames start to penetrate in wide channels too. Such behavior can be explained by the results of numerical simulations of non-reactive flow in multi-channels geometry which predict lower mixture velocity at the outlet of narrow channels compared with velocity at the exit of wide channels.

Numerical simulations were performed for equally sized channels of size 0.3 and 0.1 cm as well as for alternating channels with transverse sizes 0.3 and 0.1 cm. These conditions correspond to experimental configurations I-III. Numerically obtained regime diagram for $\phi = 0.8$ is shown in Fig. 3b. As it is seen from Fig. 3 the computational results are in a good qualitative agreement with experimental data. For configurations I and III burner stabilized flames are observed at high inlet velocities. With decrease of inlet velocity the upstream flame propagation take place. Temperature distributions typical for different combustion modes in configuration III are shown in Fig. 2. For configuration II numerical simulations predict the existence of burner stabilized flames only while in experiments the flame stabilization inside the channels is also possible (rectangles in Fig. 3a). This may be explained by the effect of external heat losses from the side surfaces of the burner which play an important role in formation of non-planar flame topology and hence in flame stabilization but is omitted in numerical simulations. Results of numerical simulations and their comparison with experimental data suggest that regions of existence of submerged stabilized flames (rectangles in Fig. 3) may largely depends on burner's linear dimensions and conditions of heat exchange with ambient.

5 Conclusions

Experimental investigations of flame penetration inside the multi-channel burners consist of equally sized narrow channels as well as of channels with different inner sizes demonstrate a big variety of combustion regimes including burner stabilized flames, upstream propagating flames and flames stabilized under the burner external surface. The regions of existence of different combustion regimes in equivalence ratio / mixture flow rate plate were experimentally found for different channels configurations. The effect of channels sizes and their mutual arrangement on flame behavior and combustion regimes were studied. It was demonstrated that at qualitative level the flames behavior in multi-channel system can be described in the frame of reduced thermal-diffusion model with prescribed flow field.

In wide range of parameters such as equivalence ratio, mixture flow rate and channels transverse size the flame pulsations having the same nature and characteristic features as FREI phenomenon [7] were observed. These pulsations are accompanied with noticeable sound and probably allow to explain the nature of noise frequently appearing in filtrational gas combustion. Information on topology and behavior of the flames stabilized inside the channels near their outlet may be useful for understanding of fundamental mechanisms of flame stabilization in the vicinity of external surface of porous burners.

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