Theoretical and experimental study of cellular structures in restricted filtration combustion of porous media

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Abstract. Infiltration-mediated combustion of a thin porous cylinder in reactive gas was studied by mathematical modeling. Gas reagent is infiltrated through an annular gap left of the side surface. In conditions of instability, the self-sustained propagation of individual cellular spots of exothermic combustion was observed. The structure of cellular waves, their dynamics, and travel direction are defined by such factors as temperature profile, pressure gradients, heat release rate, porous structure, and heat losses. Cellular combustion of Ti powder in dish was also explored experimentally and the results were compared with theoretical predictions.

1. Introduction

Still back in the 60s, Zel’dovich and Barenblatt [1] have demonstrated that the process of flame propagation in gases can be spasmodically interrupted upon temperature decrease below some critical value. In the case of solid-state combustion, critical conditions for flame propagation are complicated by front instability phenomena and formation of periodic wave propagation modes [2]. According to Aldushin [3], the extent of conversion in infiltration-mediated combustion initially grows with increasing heat losses and then the blow-out of combustion takes place upon reaching complete conversion. In conditions of unsteady infiltration combustion, an initially planar combustion front was found to degenerate into several self-sustaining hot spots of cellular combustion [4–6].

This work was aimed at the theoretical and experimental study of cellular combustion of porous thin disk in conditions of restricted supply of gas reagent.

2. Mathematical model

The nonlinear dynamics of the filtration combustion front was numerically studied using a three-dimensional system of equations of filtration combustion [5, 6]. Combustion geometry is schematically presented in figure 1. Gas reagent entered through a gap at the top. After ignition at the center, an annular expanding combustion begins to propagate over a porous combustible disk (figures 1a, 1b).

The processes are described by a system of differential equations reflecting the conservation laws with the use of simplifying assumptions. We assume that the motion of the gas reagent from the outside is almost completely due to longitudinal motion along the slit, and the gas is consumed with a thin layer of porous condensed reagent in the zone of intense chemical interaction. Transverse filtration transport of the gas from the slit into the interior of the thin layer is under almost isobaric conditions. The
longitudinal filtration of the gas in the porous layer is neglected. In the mathematical analysis, the parameters of the considered system were chosen so that, in the front propagation at insignificant heat losses, the conversion of the condensed phase is incomplete. The proposed mathematical model is similar to the model of thermal diffusion combustion of gases, and, consequently, the characteristics of the frontal exothermal chemical conversion (cellular structure of the flame front for gases and porous media) may have common features.

![Figure 1](image1.png)

**Figure 1.** Experimental setup: 1 cylindrical tray (inner $\varnothing$ 70 mm), 2 silica shield, 3 supports, $d$ gap width (2 mm), 4 igniting coil, and 5 layer of Ti powder (2 mm thick, mean particle size below 100 $\mu$m).

On going outward (figure 2a), the combustion loses the stability and degenerates into a pair of hot spots that move toward the incoming gas flow (figure 2b). Because of gas deficit, one of the cells disappears (figure 2c), while the remaining one continues its motion (figure 2d). The distribution of temperature in hot spots in conditions of low heat losses is shown in figure 3.

![Figure 2](image2.png)

**Figure 2.** Evolution of cellular combustion over a combustible porous disk, $\theta$ is the temperature.
Upon reaching the disk edge, the hot spot divides into three independent cells: two moving into different directions while the third one toward the disk center (figure 3).

3. Experiment
To check the predictions of the model, we carried the combustion in the experimental setup shown in figure 1. Providing a visual access to combustion processes, we study the filtration combustion of a thin layer of an energetic porous composition. The layer thickness is determined by temperature uniformity and good permeability for the gas reagent in the transverse direction. The porous layer should be on an insulating inert substrate with a possibility for controlling the heat transfer process between them. It is reasonable to implement filtration of the active gas reagent from the outside through the slit between the layer of the porous condensed reagent and the transparent flat wall located parallel to the porous layer at an adjustable distance. The location and nature of the motion of cells of an intense exothermic chemical conversion depend on the conditions of the combustion process and heat and mass transfer with the environment. This is confirmed by experiments carried out in a circular Duralumin bath (inner diameter of 70 mm). The titanium powder filled the bath to the upper edge, the combustion process was initiated in the center of the circle, and the gap for the supply of the gas reagent was located at its periphery because the glass was lifted above the bath by means of small screws. Initially, we observed the formation of an expanding high-temperature source of filtration combustion provided by the active gas reagent because of its great curvature. As it expanded, the inside of the source reacted completely. Cells formed at the outer edge of the expanding combustion region separated from the front (Fig. 4a), and independently propagated toward the gas flow. The number of such cells increased, and the circular symmetry was destroyed. A set of cells of exothermic conversion moving over the titanium layer was formed. They moved to the periphery, “aiming” to provide themselves with a necessary amount of active gas. Naturally, the area of unreacted titanium layer in the bath decreased, and some of the cells die (figures 4b, 4c). After the last cell disappeared, the entire bath with reacted and unreacted titanium “islets” cooled (figure 4d). The trails of the cells can be studied in detail from changes in the color of the titanium layer.

![Figure 3. Temperature distribution in hot spots in conditions of low heat losses.](image)

![Figure 4. Still frames of combustion over a 7-mm sublayer of titania used as heat insulation; time elapsed from the onset of combustion: (a) 14, (b) 30, (c) 46, and (d) 72 s.](image)
Figure 4 presents the still frames of Ti powder combustion in atmospheric air over a 7-mm sublayer of titania placed beneath sample 5 used as heat insulation. Comparison shows that theoretical predictions qualitatively agree with experimental results.

4. Conclusions
Evolution in a mode of combustion propagation is defined by not only infiltration of gas reactant, heat/mass exchange with environment but also by combustion geometry. Our results shed new light on the non-linear dynamics of combustion in heterogeneous systems and also on the character of critical conditions for combustibility limits.

References
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