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Cellular structure of a hydrogen-air flame in a channel above a porous layer

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The paper presents the results of an experimental study of the cellular structure of a hydrogen-air flame propagating in a channel with a diameter of 54 mm, partially filled with porous material. Based on the results of shadow visualization of the flame, cell size distributions in a channel with different fillings of steel wool were obtained. It is shown that the average value and standard deviation of the flame cell width in a hydrogen-air mixture with a hydrogen content of 15 vol.% in a channel filled with steel wool for 66% of the cross-section are 2.5 times less than similar ones in a channel without filling.

Keywords: hydrogen, combustion in a channel, distribution function, cellular flame, porous layer.

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The formation of a cellular structure of a flame front is one of the manifestations of its instability. The chemical reaction zone of a wrinkled flame is larger in volume than the one of a smooth flame [1]. The increase in flame velocity in the process of development of a cellular structure is related to this. Thus, one may control the flame propagation velocity by affecting the development of a cellular structure.

At the same time, the problems of combustion in limited volumes and in the presence of disperse materials of various geometries and characteristics remain relevant. For example, the quenching of a detonation combustion wave interacting with air-filled cavities was investigated numerically in [2]. The decay of a detonation wave propagating through a space filled with rods circular in cross section was examined (also numerically) in [3]. The authors of [4,5] studied the emergence of an unstable combustion regime in a porous medium. The processes accompanying the transition of a flame front from free space to a porous medium were examined in [6,7].

The development of inhomogeneities at a flame front may have a significant impact on the propagation of both a spherical flame front [8,9] and a flame front in a narrow gap [10]. Thermoacoustic instability is one of the sources of development of such inhomogeneities [11]. A porous coating on the inner surface of a channel may affect the propagation of acoustic disturbances, altering significantly the flame front dynamics.

It is critical for explosion prevention in the case of flammable gas leakage and for stabilizing combustion modes in burner devices to establish control over the flame front dynamics. While safety tasks require reducing the flame front velocity (by absorbing heat from combustion products) and minimizing the flame front area, the problem of burner device stabilization consists in maintaining combustion parameters at the most constant level possible, which is also complicated by the flame front instability.

The aim of the present study is to examine the influence of partial filling of a channel with a porous material on the cellular structure of a flame front in a hydrogen-air mixture.

An experimental setup with a control panel for preparing a combustible mixture and a plexiglass tube with a built-in spark discharger and a gas injector was assembled in order to visualize the flame front in the tube. The combustion of a hydrogen-air mixture with 15 vol.% of hydrogen was studied in the transparent 500-mm-long tube open on one end with an internal diameter of 54 mm and a wall thickness of 3 mm. The tube was purged with a volume of 0.025 m^3, which exceeds the tube volume by a factor of more than 20, to fill it with the combustible mixture. A spark with an energy of 50 mJ positioned on-axis in the cross section of the open end of the tube ignited the mixture. The tube was monitored with an IAB-451 shadow instrument with a visible region 230 mm in diameter. The flame propagation was recorded using a Phantom VEO 710S high-speed video camera.

Figure 1 shows typical shadow images of the flame front in the tube without filling and with a porous material layer of two different thicknesses. Steel wool with a porosity of 99.7% and a fiber thickness of 100 μm was used as this porous material.

The propagation of a cellular flame toward the closed end of the tube is seen in Fig. 1. The open fraction of the tube cross section is 100, 66, and 21%. Judging by the overall slope of the flame front, the combustion rate in the porous material is higher than in the free part of the tube. Owing to a lower rate of growth of the volume of combustion products, heat losses definitely reduce the flame velocity. The flame in the porous layer is fragmented and turbulent in this case. In the free volume, the effect consists only in

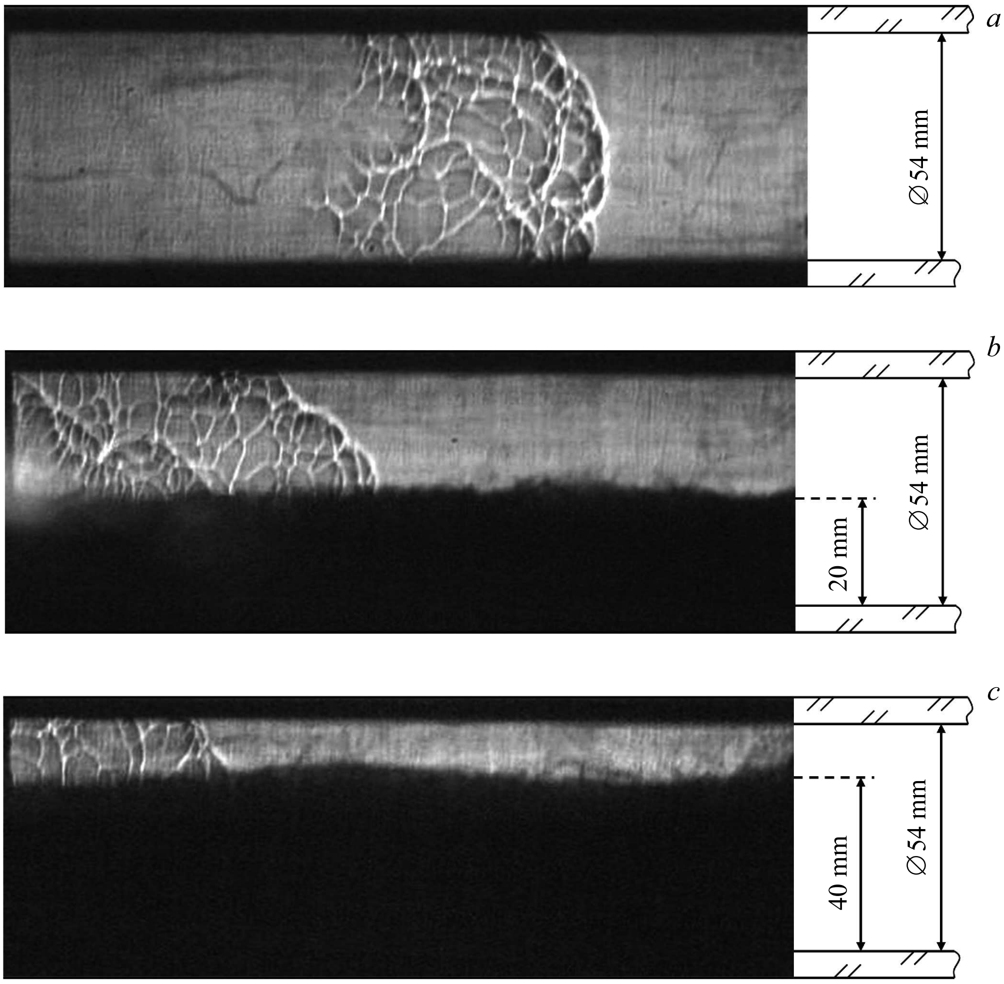

Figure 1. Shadow images of a cellular flame front in a channel with no porous material or filled partially with a porous material. *a* — Channel with no porous material, the time is 140 ms; *b* — channel with a 20-mm-thick porous material, 140 ms; and *c* — channel with a 40-mm-thick porous material, 200 ms.

absorption of heat from combustion products, which leads to a reduction in the average expansion coefficient. The results reveal that the experimentally recorded flame propagation velocity in a partially filled channel increases in the porous layer region.

The transverse dimensions of cells were measured as the distances between the arc ends or the crests at junctions of adjacent cells. We were able to detect and measure correctly up to 50 transverse cell sizes based on all the available frames in each experiment.

The histogram of the distribution of all cell sizes is shown in Fig. 2. The experimentally determined numbers of cells in different size ranges were approximated by a normal distribution function. The curves reveal a reduction in the average transverse cell size and the standard deviation of the distribution function with an increase in thickness of the steel wool layer. Specifically, when a flame propagates in the free tube, the average cell width is 10.7 mm and the standard deviation is 2.63 mm. These values change to 7.2 mm and 1.76 mm if a flame propagates above a steel wool layer 20 mm in thickness. When the steel wool layer thickness increases to 40 mm, the average cell width is 4.34 mm and the standard deviation is 1.55 mm. The ratio of the standard deviation to the average value is 0.25, 0.24, and 0.36 in these cases; i.e., the relative spread of cell sizes increases at high tube fill factors.

The influence of the cellular structure on the flame velocity may be estimated using the approach detailed in [12]. The flame front velocity in the free part is, as a first approximation, proportional to the ratio of the flame area to the channel area. If the cell size drops below $2\lambda_{DL}$, where λ_{DL} is the minimum size of a growing cell (approximately 2.5 mm for a 15 vol.% hydrogen-air mixture), the rate of growth of the cell amplitude decreases, which translates into a lower flame propagation velocity.

Thus, a series of comparative experiments on the flame front propagation in a channel filled partially with steel wool were performed. Shadow photographs of flame propagation were used to obtain size distributions of flame cells. The cell size decreases by a factor of 1.5 and 2.5 in the case

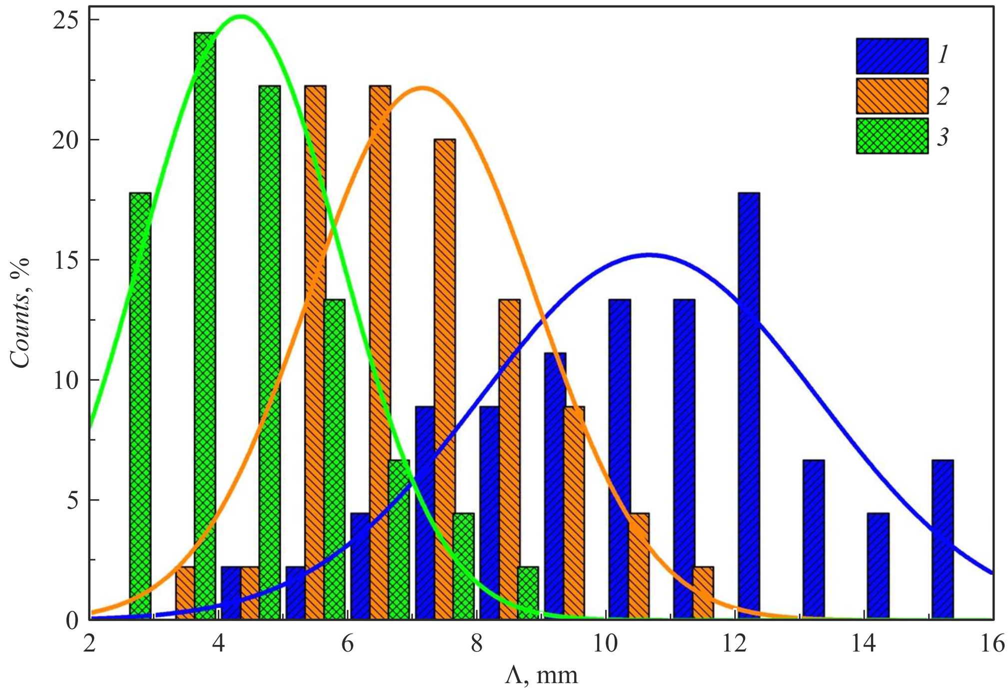

Figure 2. Distributions of flame cell sizes Λ and their approximations by normal distribution functions (probability density). *1* — Flame in a free channel; *2* — flame over a 20-mm-thick steel wool layer; and *3* — flame over a 40-mm-thick steel wool layer.

of propagation above a porous layer 20 and 40 mm in thickness, respectively.

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Conflict of interest

The authors declare that they have no conflict of interest.

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