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Influence of acoustic oscillations on the speed of a cellular hydrogen-air flame in a horizontal channel

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The results of an experimental investigation of the effect of acoustic oscillations with a frequency of 250−7000 Hz and an intensity of 105 dB on the dynamics of the acceleration of a hydrogen-air flame in an open channel are presented. Dependences of the position of the flame front and cell sizes were obtained from shadow photographs at different frequencies of acoustic oscillations. The frequency values when the average flame speed increases up to 3 times are found. Acoustic action with a frequency of 250 Hz leads to a slight decrease in the speed of the flame.

Keywords: Hydrogen, duct combustion, acoustic impact, cellular flame.

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Methods of influencing combustion of gas mixtures in channels are in demand in energy applications and in explosion safety problems. Effect of pretreatment of a stoichiometric hydrogen-air mixture on propagating detonation wave characteristics has been investigated numerically in paper [1]. The role of organosilicon fluid additives for stabilizing supersonic combustion of hydrocarbon fuels is shown in [2]. One of promising methods to influence combustion parameters is the acoustic influence on the flame region. In [3] analytically, and in [4] experimentally, influence of acoustic gas oscillations on the flame propagation in the vertical direction is shown. In [5] the possibility of stabilizing and increasing the intensity of turbulent combustion of methane-air mixture in the flare with the help of external oscillations is shown. In [6] acoustic influence on the area of diffusive jet combustion of methane in air made it possible to reduce the content of soot and nitrogen oxides in the combustion products. The present paper is dedicated to influence of acoustic oscillations on the propagation of the flame front in a hydrogen-air mixture in a horizontal channel of circular cross section.

To determine the external acoustic influence on gas flame propagation, a series of experiments on hydrogen-air flame propagation in a circular cross-section channel with a diameter of 54 mm and a length of 520 mm were performed. An experimental setup for studying the hydrogen-air flame front propagation in open-end tubes consists of a gas pre-mixing system, a system for purging a tube with a combustible mixture, and a high-speed shadow imaging system. The hydrogen-air mixture was prepared in a 40 liter cylinder. Gases were fed from a compressor and a hydrogen cylinder of 99.999% purity. The gas volume was regulated by a pressure gauge with error of 800 Pa. Maximum pressure in the reservoir with the mixture reached 500 kPa. The cylinder was first emptied to the limit value of vacuum pump 1.1 Pa, and then filled with air and hydrogen. The prepared mixture was allowed to stand in the cylinder for at least 24 h before the experiments.

The channel was purged with 10 liters of combustible mixture before ignition. The volume of the mixture was monitored using a Bronkhorst El-Flow flow meter. Thus, the volume of mixture for purging was 10 times the volume of the channel. Ignition was performed in the center of the closed end of the channel by a spark with an energy of 50 mJ. Acoustic oscillations were created by a dynamic head located at a distance of 150 mm from the open end.

Visualization of combustion was carried out by a shadow device IAB-451 with registration by a high-speed video camera Phantom VEO 710 S. The light source for shadow imaging was a xenon lamp. A 150 mm long window was cut into the Plexiglas channel to achieve maximum transparency for shadow imaging. A 0.2 mm thick transparent PET film was placed in each window. The speed camera recorded at 1000 frames per second.

Three experiments were performed each with no sound and with sound intensity of 105 dB and frequencies of 250, 350, 700, 800, 1500, 3500, and 7000 Hz. As a result, a series of shadow photos of the flame front in the channel were obtained (fig. 1, *a*). Based on a series of shadow photos the time dependences of the flame front position were plotted (fig. 1, *b*).

From the dependences shown in fig. 1, *b*, it can be seen that the acoustic exposure with frequency of 250 Hz leads to a slight decrease in the flame speed. Impacts with frequencies of 350, 700, 3500 and 7000 Hz lead to a maximum acceleration of the flame. Impacts with frequencies of 800 and 1500 Hz show an average acceleration between the one obtained in the experiment without impact and the maximum acceleration.

In the exposure of gases combustion to acoustic oscillations in a tube closed at one end, we can distinguish two main mechanisms: changing the transfer coefficients and the

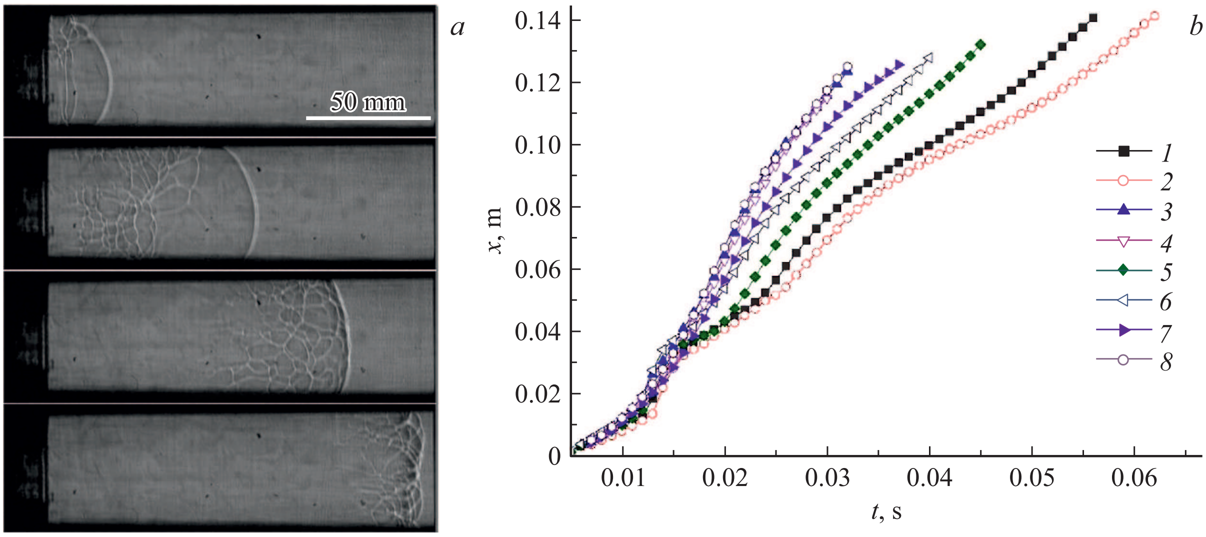

Figure 1. *a* — consecutive shadow photos of the flame propagation in a hydrogen-air mixture with hydrogen content of 15 vol.% when exposed to acoustic waves with a frequency of 3500 Hz at time moments 15, 25, 35 and 45 ms (from top to bottom) after ignition. *b* — dependences of the average channel position of the flame front as a function of time at different frequencies of acoustic influence and without it: *1* — without exposure, *2* — 250 Hz, *3* — 350 Hz, *4* — 700 Hz, *5* — 800 Hz, *6* — 1500 Hz, *7* — 3500 Hz, *8* — 7000 Hz.

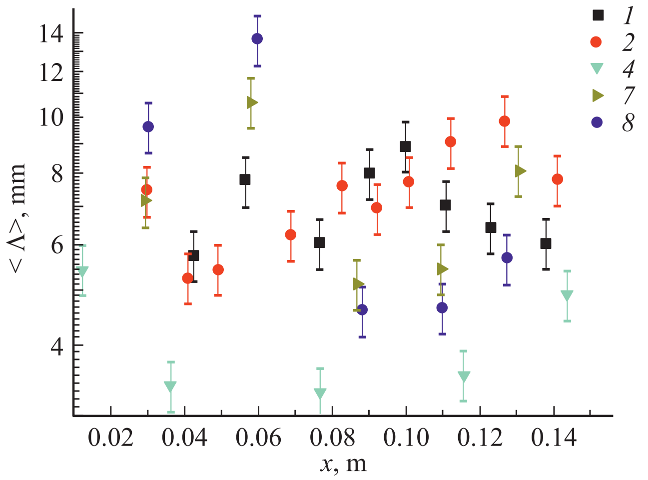

Figure 2. Dependences of the average cell width on the distance traveled by the flame front, at different frequencies of acoustic influence and without it: *1* — without action, *2* — 250 Hz, *4* — 700 Hz, *7* — 3500 Hz, *8* — 7000 Hz.

creation of flame front disturbances. Change in the transfer coefficients in the gas occurs due to the formation of areas with increased and decreased pressure. A calculation using the [7] method demonstrated that in the investigated range of frequencies and sound intensities, the relative change in the normal combustion rate is less than $6 \cdot 10^{-7}$. To reduce the normal combustion rate by 1%, a pressure pulsation value of 40 kPa is required, which is beyond the range of sound oscillations. Thus, the effect of acoustic oscillations of the gas mixture on the laminar burning velocity can be neglected.

The main effect of the three-dimensional structure of the flame front on its velocity is to increase the area of the flame front, and hence the mass consumption rate of the combustible mixture.

When the flame front propagates through the channel, depending on the frequency of sound exposure, the characteristic width of the cells changes. Fig. 2 shows the dependences of the average value of the cell width measured from the shadow photographs on the distance traveled by the flame front.

An analytical solution presented in paper [3], shows complete suppression of Darrieus–Landau instability at frequency of acoustic oscillations 3500 Hz, and parametric instability of flame develops at the same time with cell size of 3 mm. From fig. 2 it is seen that cells of such size are only observed at frequency of acoustic oscillations of 700 Hz. When exposed to a frequency of 3500 Hz the width of the cell is 5 mm and above. At exposure frequencies other than 700 Hz, no significant decrease in cell width was found.

The cell flame propagation velocity can be calculated using the methodology outlined in [8]. After reduction to a single formula, the dependence of the flame velocity on the width of the cell will be:

$$v = \Theta S_L^0 \left(1 + \frac{8\pi^2 L_M^2}{\Lambda^2} - \frac{32\pi^3 L_M^3}{\Lambda^3(\Theta - 1)} \right),$$

where Θ — coefficient of thermal expansion of combustion products, S_L^0 — normal combustion velocity, L_M — Markstein length for a combustible mix, Λ — cell size.

Fig. 3 presents dependences measured and calculated by cell width between the flame front velocity and distance travelled at variosu frequencies of acoustic exposure and without such. It can be seen that under acoustic influence

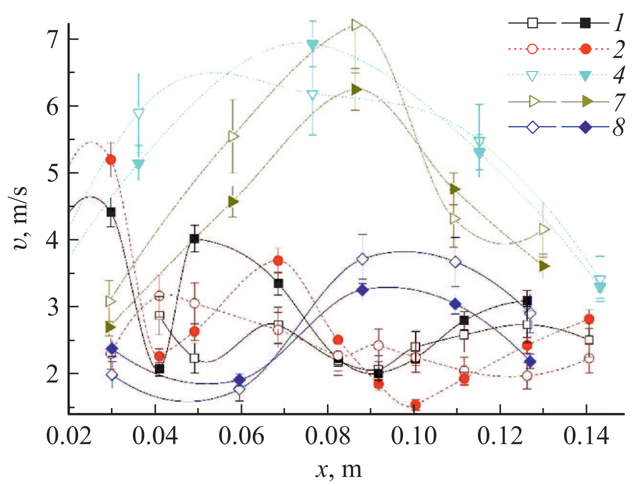

Figure 3. Dependences of the flame front velocity on the distance traveled at various frequencies of acoustic exposure and without such: *1* — without action, *2* — 250 Hz, *4* — 700 Hz, *7* — 3500 Hz, *8* — 7000 Hz. Colored symbols — experimental values of velocity, uncolored — calculated on the basis of cell width.

with frequencies of 700 and 3500 Hz the flame speed increases up to 3 times compared with experiments without exposure. At a distance greater than the diameter of the channel, when the flame form occupies the entire cross section, the calculated values of the flame velocity differ little from the measured ones. Thus, under the experimental conditions, the change in the cellular structure of the flame front can be considered as the main mechanism of the influence of acoustic oscillations on the combustion rate.

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Conflict of interest

The authors declare that they have no conflict of interest.

References

[1] V.A. Levin, T.A. Zhuravskaya, Tech. Phys. Lett., **46** (2), 189 (2020). DOI: 10.1134/S1063785020020248.
[2] S.V. Kolosenok, A.L. Kuranov, A.A. Savarovskiy, P.V. Bulat, A.A. Galadzhun, A.A. Levikhin, A.B. Nikitenko, Pisma v ZhTF, **47** (19), 19 (2021) (in Russian). DOI: 10.21883/PJTF.2021.19.51507.18764
[3] V. Bychkov, Phys. Fluids, **11** (10), 3168 (1999). DOI: 10.1063/1.870173
[4] B. Radisson, J. Piketty-Moine, C. Almarcha, Phys. Rev. Fluids, **4** (12), 121201 (2019). DOI: 10.1103/PhysRevFluids.4.121201
[5] S.V. Alekseenko, V.M. Dulin, Yu.S. Kozorezov, D.M. Markovich, Tech. Phys. Lett., **37** (3), 278 (2011). DOI: 10.1134/S1063785011030187.
[6] M.S. Krivokorytov, V.V. Golub, V.V. Volodin, Tech. Phys. Lett., **38** (5), 478 (2012). DOI: 10.1134/S1063785012050240.
[7] A.E. Dahoe, J. Loss Prev. Process Ind., **18** (3), 152 (2005). DOI: 10.1016/j.jlp.2005.03.007
[8] S.S. Minaev, Combust. Explos. Shock Waves **28**, 30 (1992).