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INVESTIGATION OF THE DYNAMIC PROPERTIES OF THE CELLULAR STRUCTURE OF A GAS-DETONATION WAVE

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The evolution of the cellular structure of a gas-detonation wave propagating in a circular pipe was investigated. The propagation regimes, hereafter "detonation modes," for which the organization of the flow in the detonation-wave front and, accordingly, the shape of the cellular structure have the best symmetry and recurrence, have been revealed. It is shown that the realization of only the single-mode regime of propagation is improbable and that the complete state of the wave-front structure as a function of time can be represented as a superposition of periodic functions corresponding to the states of neighboring detonation modes, and their normalized amplitude is proportional to the probability of the presence of the state of a given mode when a gas-detonation wave propagates.

The detonation-cell size is one of the most important parameters characterizing the structure and macroscopic properties of the gas-detonation wave [1-3]. Despite the great number of investigations concerned with the study of the internal structure of detonation waves, data on the processes of structural reorganization of the detonation front, arising as it propagates during a fairly long period of time, have practically been unavailable to date. Below are the results of an experimental investigation of the mechanisms of the cellular-structure evolution in acetylene-containing combustible gas mixtures of different degree of "regularity" [4] in the case of propagation of a detonation wave along a circular pipe with a fixed cross section.

Along with the traditional trace technique [5] for obtaining data on the dynamics of structural changes in the detonation front, we used the contactless emission method [6], which is based on photoelectric detection of the intensity of the intrinsic luminescence of the gas in several directions perpendicular to the wave front. In this case, the amplitude and frequency modulation of the emission-signal intensity in the direction of detection were determined by the special properties of the combustion of the combustible mixture, generated by the periodic motion and interaction of transverse detonation waves. Both the current and mean values of the longitudinal size (length) of the detonation cell were determined for each direction by multiplying the time interval between neighboring maxima or minima of the intrinsic-luminescence intensity by the detonation-wave velocity. The numerical value of the time interval was determined from the recorded signals by two different methods: through direct successive measurements and through determination of its most probable value by analyzing the Fourier spectrum of the shape of intrinsic luminescence signals.

Experimental Setup. The experimental setup described in detail in [6] was based on a detonation pipe with a length of 3.7 m and an inside diameter of 25.5 mm. The process of initiation of detonation in the main channel was effected by combustion products formed in the explosion of a $C_2H_2 + 2.5O_2$ stoichiometric mixture in the unit for prechamber ignition. This unit was set at the inlet to the main channel of the detonation pipe, and its length was 60 mm. The region of the pipe used for emission measurements was positioned near the outlet section of the detonation channel and extended into it for 805 mm. The end of the detonation pipe was equipped with a flange having a built-in plane-parallel quartz window whose dimensions provided a complete view of the interior volume of the detonation channel. The choice of the directions for measurement of the intrinsic-luminescence intensity and their orientation relative to the axis was made by a field diaphragm set

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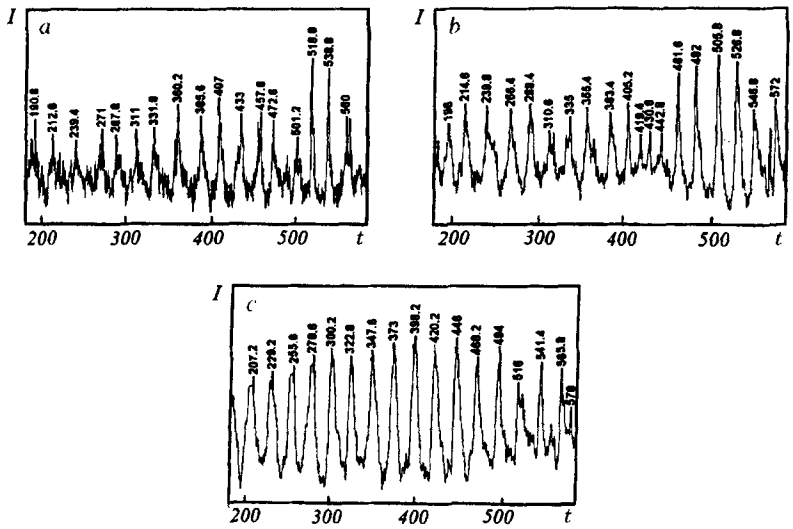

Fig. 1. Intensity of the intrinsic luminescence of a gas as a function of time for three directions of recording: two directions are positioned near the opposite walls of the detonation channel [a) top; b) bottom], the third direction is coincident with the detonation-pipe axis [c) center] (a 3.5% C_2H_2 + 26.5% O_2 + 70% Ar mixture, the initial pressure is P_0 = 140.5 mm Hg). I, rel. units; t, μsec.

directly behind the quartz window. For comparison with the results of the trace method, two directions were positioned near the opposite walls of the detonation-pipe channel, and the third direction was coincident with its axis. Figure 1 shows the characteristic dynamics of the change in the intensity of the intrinsic luminescence of the gas mixture behind the detonation-wave front. It is seen that the amplitude-frequency modulation of the emission signals makes it possible to perform a reliable detection of the detonation-front structural reorganization in the real time regime. The optical scheme for recording the intrinsic-luminescence intensity provided a spatial resolution of up to 2.7 mm at the initial point of the measured region: it improved as the wave moved to the outlet section of the detonation pipe. The emission signals were detected with the help of photomultipliers and were recorded with a time resolution of up to 0.2 μsec on digital oscillograms interfaced with a personal computer.

To obtain trace impressions of the propagation of the detonation-wave front, we used a transition unit 320 cm in length with a circular cross section. The unit was provided with a special facility for fastening of smoked films and was connected to the end of the detonation channel with no change of the flow section. Under certain conditions the measuring system used made it possible to simultaneously perform the photorecording of the intrinsic-luminescence signals and to obtain the trace impressions.

The influence of the chemical composition on the dynamic features of the detonation-front propagation was investigated in accordance with the classification of gas mixtures with different degree of "regularity" of the cellular structure. In this work, we used a 3.5% C_2H_2 + 26.5% O_2 + 70% Ar regular mixture [7] and a C_2H_2–air irregular stoichiometric mixture.

Results. The influence of the initial pressure on the dynamic properties of the cellular structure that manifest themselves when a detonation wave propagates in the 3.5% C_2H_2 + 26.5% O_2 + 70% Ar regular mixture was investigated in detail with the help of the emission and trace methods near the walls and on the axis of the detonation-pipe channel. The mean value of the detonation-cell longitudinal size, obtained from the measurement of the time interval between the maximum values of the intrinsic luminescence intensity (Fig. 2), is in good agreement with the data of the trace method and the results obtained in [7].

It was established that at the center and at the periphery of the detonation pipe the forms of the spatial organization of an explosive ignition giving rise to a new cell are very different. If, on the pipe axis, the in-

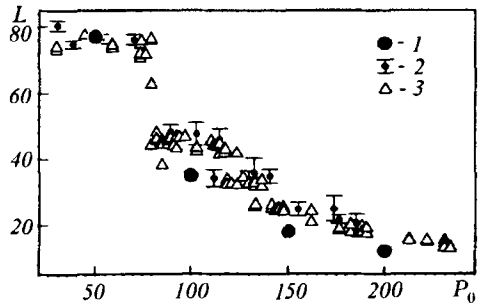

Fig. 2. Mean value of the detonation-cell length as a function of the initial pressure: 1) results of [7]; 2) measurements by the trace method; 3) measurements by the emission method near the detonation-channel wall (a 3.5% C_2H_2 + 26.5% O_2 + 70% Ar mixture). L, mm; P_0, mm Hg.

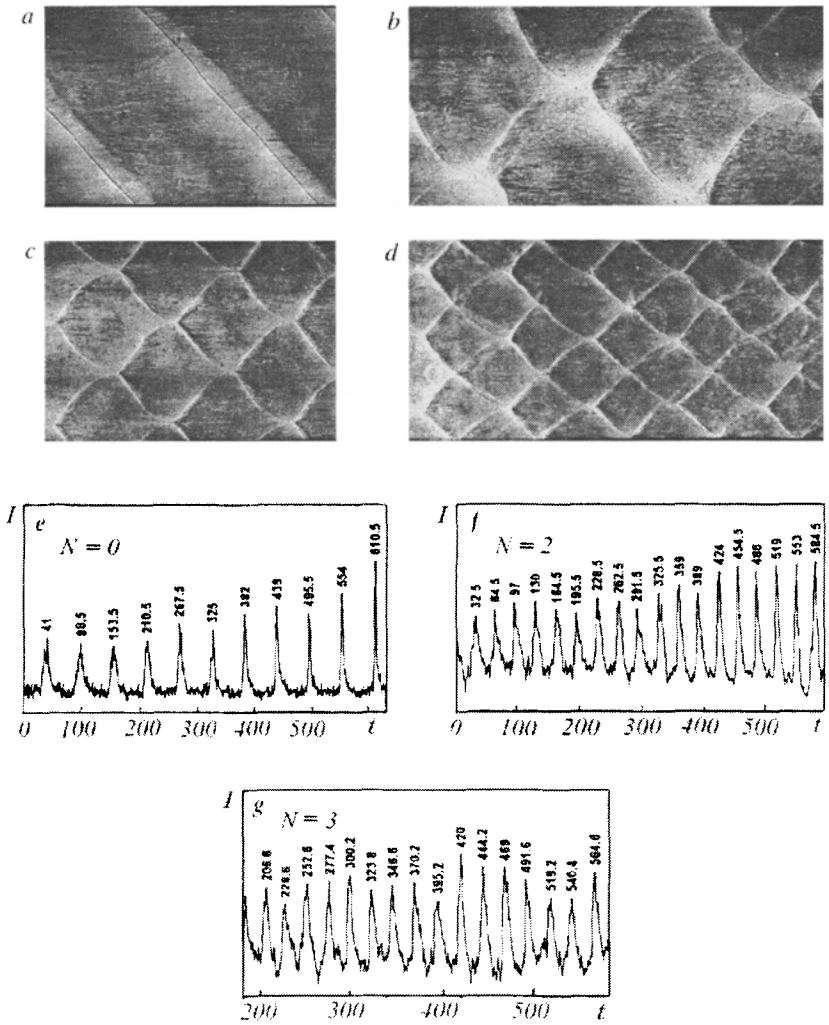

Fig. 3. Trace impressions of states of the detonation-wave-front structure for detonation modes with orders: N = 0, P_0 = 45.6 mm Hg (a), 1 and 90.6 (b), 2 and 114 (c), and 3 and 152 (d), and results of photoelectric recording of the intrinsic-luminescence intensity: e) N = 0, P_0 = 60.8; f) 2

Fig. 4. Trace impressions of states of the detonation-wave-front structure for detonation modes with the following orders: a) $N = 0$, $P_0 = 53.2$ mm Hg; b) 1 and 139.8; c) 2 and 158.1 (a C_2H_2–air stoichiometric mixture).

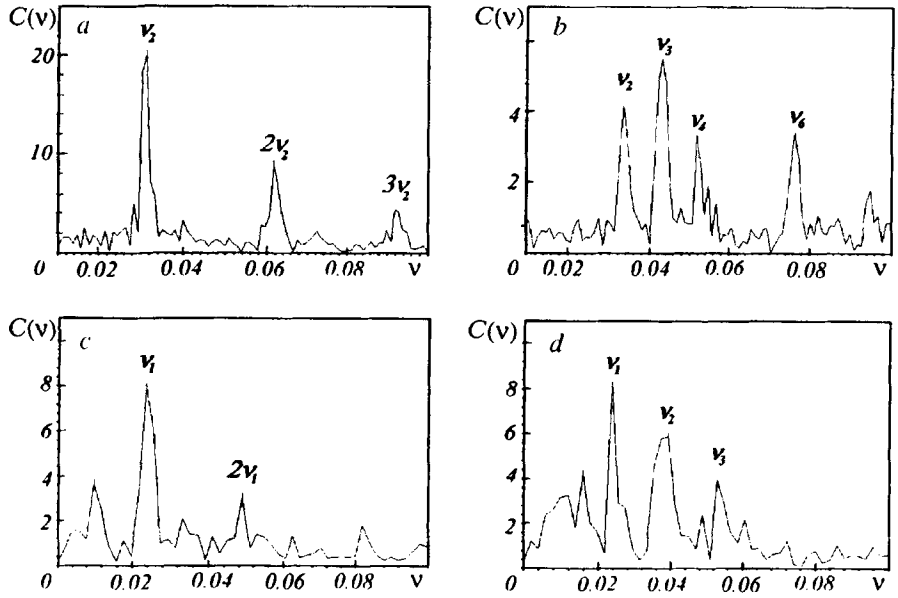

Fig. 5. Fourier spectrum of the shape of intrinsic-luminescence signals: a) regime of the detonation mode $N = 2$, $P_0 = 115.5$ mm Hg (a 3.5% C_2H_2 + 26.5% O_2 + 70% Ar mixture); b) regime of mode mixing with $N = 2$, 3, 4, and 6, $P_0 = 127.6$ mm Hg (a 3.5% C_2H_2 + 26.5% O_2 + 70% Ar); c) regime close to the detonation mode, $N = 1$, $P_0 = 91.2$ mm Hg (a C_2H_2–air stoichiometric mixture); d) regime of mode mixing with $N = 1$, 2, and 3, $P_0 = 176.3$ mm Hg (a C_2H_2–air stoichiometric mixture).

itiation is due to the three-dimensional radial compression of the combustible mixture, at the surface the process of two-dimensional reflection of transverse waves from the walls of the detonation channel is of primary importance. As a result, at a distance that corresponds to the characteristic longitudinal dimension of the detonation cell, both the time and the intensity of the energy release are different in different regions of the transverse cross section of the channel. The arising energy disbalance is the main source of the internal instability of the detonation-wave front and a stimulator of its structural reorganization.

Nevertheless, under certain conditions that depend on the initial pressure of the investigated mixture the occurrence of specific regimes of detonation propagation in the channel, hereafter "detonation modes," becomes probable. In this case, for a certain time the rate of energy release inside the detonation-front elements is strictly synchronized with the gas-dynamic scheme of the flow organization, while the cellular-structure shape mapped on the trace impressions has the highest type of symmetry and recurrence. The observed magnitude of the relative mean-square deviation of the detonation-cell longitudinal size, obtained from the analysis of the emission signals and trace impressions in the 3.5% C_2H_2 + 26.5% O_2 + 70% Ar mixture, is 1–3%. In turn, the transverse size of the cell in measuring on the inner surface of the detonation channel by the trace method is found to be equal to $\lambda = \pi d/N$, where d is the pipe diameter, and N is an integer, detonation-mode order.

In the case where the detonation-mode number is $N > 0$, the probability of realization of the state of only one mode over the total length of the detonation channel is small. In this connection, considerable efforts

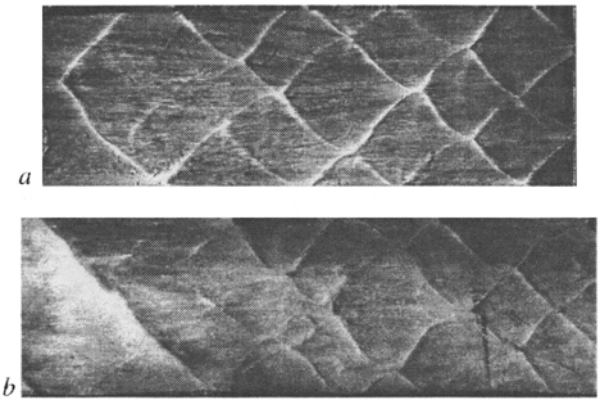

Fig. 6. Trace impressions of the flow-structure reorganization in the detonation-wave front from one mode to another: a) regime of transition from $N = 2$ to $N = 1$, $P_0 = 88.16$ mm Hg (a 3.5% C_2H_2 + 26.5% O_2 + 70% Ar mixture); b) regime of transition from $N = 2$ to $N = 1$ and then to $N = 0$, $P_0 = 142.9$ mm Hg (a C_2H_2–air stoichiometric mixture).

went into the detection of the states of the cellular structure of the detonation-wave front that correspond to different values of the mode number N with the help of the trace and emission methods. Figure 3 shows trace impressions and intrinsic-luminescence signals for detonation modes of different order, obtained in the 3.5% C_2H_2 + 26.5% O_2 + 70% Ar mixture. An investigation of the dynamic properties of the cellular structure in the classically "irregular" C_2H_2–air stoichiometric mixture showed that the occurrence of detonation modes in the channel is independent of the degree of "regularity" of the mixture, and regimes of detonation propagation with different mode numbers were revealed (Fig. 4). As is seen from Figs. 3 and 4, the influence of the mixture "irregularity" results in the inner microorganization of the flow in the detonation-wave front that is reflected on the trace impressions in the form of a small-scale reticular pattern modeling the general macrostructure of the detonation cell.

The Fourier transformation of the shape of the emission signals in the investigated mixtures lent support to the view that, as a rule, the realization of only the single-mode regime of detonation-wave propagation is unlikely, and the integral dependence of the intrinsic-luminescence intensity on time over the measured zone of the detonation channel is a superposition of several harmonics that corresponds to the states of two or several detonation modes of different order. Their normalized amplitude is proportional to the probability of experimental determination of the given mode state in the course of measurements. Figure 5 shows the characteristic shapes of the Fourier spectrum of the emission signals, and Fig. 6 shows the trace impressions of the mode-mixing regimes, i.e., the reorganization of the flow structure from one mode to another. It should be noted that, because of the existence of the flow substructure, the spectral composition of the intrinsic-luminescence signals obtained in the C_2H_2–air stoichiometric mixture is more saturated in the region of high frequencies as compared with the spectrum of the 3.5% C_2H_2 + 26.5% O_2 + 70% Ar mixture.

Thus, in propagation of a gas-detonation wave, for a rather long time the structure of its front can pass a sequence of quasistationary states, each of which is characterized by the realization of a flow of a definite type – a detonation mode. The total instability of the flow in the wave front, caused by the nonuniform spatial and temporal distribution of the released energy, leads to its structural reorganization, at least at distances that correspond to the characteristic longitudinal dimension of the detonation cell. As a consequence, when a gas-detonation wave propagates in the channel, its determining dynamic parameter, i.e., the detonation-cell size, can take on a rather wide range of possible values. This leads to the disorder of the structure of the detonation-wave front even in the case of propagation of the wave in practically ideal mixtures with a high degree of dilution with an inert gas.

As a rule, the probability of detection, in the prescribed channel, of the regime of propagation with a certain value of the mode number N is dependent only on the value of the total density of the energy release,

which is completely determined by the initial pressure (density) of the investigated mixture. With its increase, the probability of appearance of detonation modes of higher order increases. Therefore, we can speak about the dependence of the detonation-cell size on the initial pressure only in the context of the probability of experimental detection of a given size in the case of measurement in a concrete cross section of the detonation pipe.

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