BEGINNING AND BUILDUP OF FLAME FLUCTUATIONS

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Results are shown of an experimental study concerning the beginning and buildup of fluctuations in a flame which travels through a horizontal semiopen duct filled with a methane–air mixture. The necessary conditions are established under which the flame fluctuations become amplified. Test results are compared with theoretical conclusions.

The authors have studied the variations in shape and surface area of a flame front during vibratory combustion of prepared reactant mixtures in ducts.

The tests were performed in a horizontal square duct 3.6 × 3.6 cm^2 in cross section and 69 cm long, made of grade AG-4s glass plastic. Into the walls at the entrance and at the exit we had installed plane-parallel panes of optical grade glass for viewing the entire duct section 21 cm deep. A hot mixture of 10% methane and 90% air was ignited at the open end of the duct. The flame front was examined by the Tepler method. The flame travel was recorded with a model SKS-1 high-speed camera at a rate of 3000-3500 frames/sec. In order to scale up the image somewhat, we used an objective with a focal length of 9.5 cm.

An evaluation of the recorded film strips has shown that through the first third of the duct length a flame travels at a constant velocity. The shape and the surface area of the flame front remain unchanged during this stage of the fluctuation buildup. After that, there begin distinct fluctuations accompanied by changes in the shape of the flame front. These changes cause changes in the distance H between the leading and the trailing edge of the flame front (in the flame front elongation) as well as in the length l of the flame boundary line recorded on a thermogram. In view of the serious difficulties with measuring the surface area of a flame, we analyzed the various process stages on the basis of dimensions H and l, which could be easily measured and which provided sufficient information about the changes in the flame surface at various stages of the fluctuation buildup. During the period of uniform flame propagation H and l remained constant. The beginning of flame fluctuations was accompanied by periodic variations in these quantities at an approximately 190 Hz frequency of flame fluctuations and by a periodic variation in their mean values at a much lower frequency.

In Fig. 1 are shown H/H_0 (curve I) and l/l_0 (curve II) as functions of time during the initial stages of the fluctuation buildup. Both H_0 and l_0 characterize an unperturbed flame front traveling at a constant velocity. The time is counted from the instant the mixture has been ignited. The mean flame velocity within the test period varies exactly as H_{mean}/H_0 and l_{mean}/l_0; it first decreases to a minimum and then increases again. Later in the process both H_{mean}/H_0 and l_{mean}/l_0 again decrease. However, those later stages of the fluctuation buildup were not considered in our study. The period of fluctuation buildup characterized by a decrease in H_{mean}/H_0 and l_{mean}/l_0 as well as in the mean flame velocity will be called the first stage, while the following period characterized by an increase in these quantities will be called the second stage.

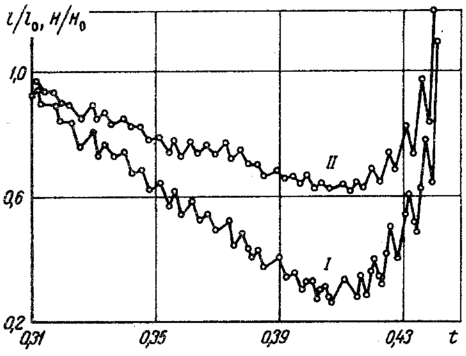

Fig. 1. Variation in H/H_0 (curve I) and l/l_0 (curve II) with time t (sec).

Thermograms of the flame front indicate that the latter remains smooth and meniscoid in shape during the first stage. Changes in the flame surface occur not within the narrow

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boundary layer but, as assumed by the authors of [1-3], over the entire duct section. The mean velocity of the flame front is a linear function of both H_{mean}/H_0 and l_{mean}/l_0. The amplitude of flame front fluctuations increases very insignificantly. Moreover, H/H_0 and l/l_0 fluctuate at an almost constant amplitude. Since the mean values of these quantities decrease with time, however, their relative variations increase.

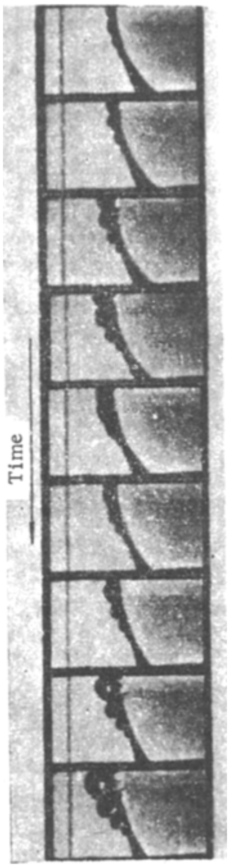

Fig. 2. Development of wave formation on the flame surface.

During the second stage the amplitude of flame front fluctuations increases. At the flame front there appear perturbations first recorded on photographs in the form of periodically brightening and fading nodes. At the same time, one observes an increase in the mean flame velocity at almost constant H/H_0 and l/l_0. Inasmuch as the mean flame velocity is uniquely related to the flame surface area, one may assume that the nodes represent a large cluster of small perturbations not individually distinguishable with available instruments. The amplitude of flame front fluctuations at the beginning of the perturbations is 2 to 3 mm. The gas velocity is here approximately 3 m/sec and its acceleration is $(3 \text{ to } 4) \cdot 10^3$ m/sec^2. The buildup and the amplification of the perturbations is illustrated by the series of photographs shown in Fig. 2. The perturbations appear initially at the flattest part of the flame front near the top wall of the duct, and then gradually encompass its entire surface. It can be seen clearly on the photographs how the perturbations increase and decrease periodically, resulting in a periodic variation of the flame front elongation. At the same time, the flame front continues to periodically elongate and flatten, just as during the first stage of the fluctuation buildup. The continuously varying flame front elongation makes it impossible to track the displacement of fixed points on the flame front. Some notion about the character of the developing perturbations can be gained by recording the displacements Δx of those points on the flame front whose excursions are largest. A variation in Δx with time for the given case is shown in Fig. 3, where Δx is expressed in millimeters. It is evident here that various points on the front oscillate in phase but with different amplitudes. This indicates standing waves on the flame surface. In some cases (Fig. 3) the number of these waves remained constant over several periods of flame front fluctuation, but their lengths varied with time at double the period of the flame front fluctuation. In other cases the number of waves on the flame surface varied at double the period of flame front fluctuation. The increase in the amplitude of flame front fluctuation during the second stage of the fluctuation buildup is related to an increase in the amplitude of flame surface fluctuation due to the simultaneous effects of a periodically varying flame front elongation and of the wave formation on the flame front surface. The effect of the first of these factors was not considered in [5].

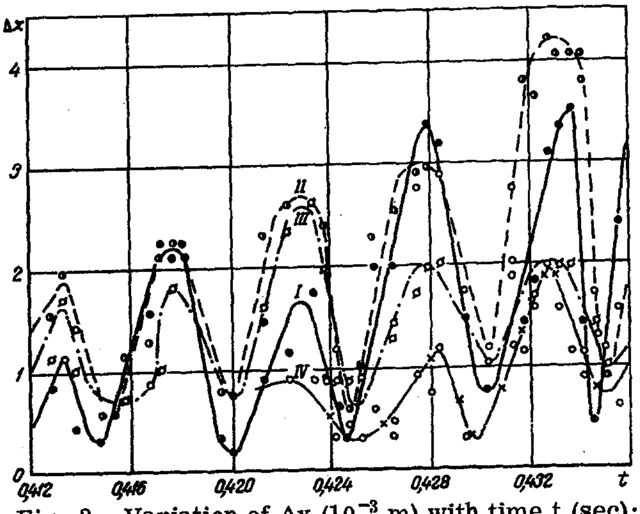

Fig. 3. Variation of Δx (10^{-3} m) with time t (sec): curves I, II, III, IV correspond to four respective standing waves on the flame surface.

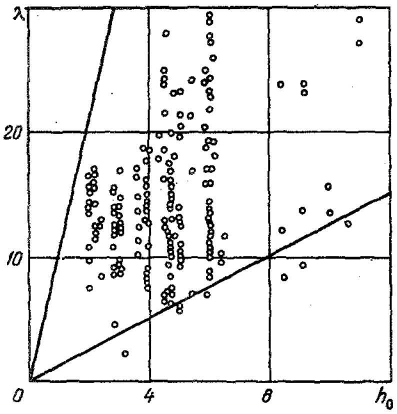

Fig. 4. Wavelength λ (10^{-3} m) as a function of the amplitude of flame front fluctuations h_0 (10^{-3} m).

The process of wave formation on the flame front may be regarded as a manifestation of a Taylor instability [6], which occurs at the interface between two liquids or two gases of different densities during an acceleration from the thinner toward the denser side. During vibratory combustion this acceleration varies periodically as a result of acoustic vibrations of the gas enclosed in the duct. The amplitude of the acceleration variations depends on the amplitude of flame front fluctuations. It has been shown in [4] that a wave begins to form most likely when

$$0.91 < 4\pi \frac{h_0}{\lambda} \frac{\rho_1 - \rho_2}{\rho_1 + \rho_2} < 7.5. \tag{1}$$

It follows from (1) that for the limits of the said instability interval the relation between λ and h_0 is

$$\lambda_{\max} = \frac{4\pi}{0.91} \frac{\rho_1 - \rho_2}{\rho_1 + \rho_2} h_0,$$
$$\lambda_{\min} = \frac{4\pi}{7.5} \frac{\rho_1 - \rho_2}{\rho_1 + \rho_2} h_0. \tag{2}$$

The straight lines in Fig. 4 represent the boundaries of the instability region (2), and the points represent test values of λ as a function of h_0 (both λ and h_0 are expressed here in millimeters). The test points fall well within the calculated boundaries. According to theory, the period of flame front shape fluctuation does not exceed the instability time interval (1) and is twice as long as the period of flame front fluctuations. The test data shown here confirm this theoretical conclusion.

We note, in conclusion, that the variation in l/l_0, which occurs at the frequency of flame front fluctuations, is always in phase with those fluctuations during the first stage of fluctuation buildup. During the second stage, in some cases the phase shift between l/l_0 variations and the flame front displacement is close to $\pi/2$.

NOTATION

H	is the distance between the leading point and the trailing point of a perturbed flame front;
H_0	is the distance between the leading point and the trailing point of an unperturbed flame front;
l	is the length of the boundary line of a perturbed flame front, as recorded by the Töpler method;
l_0	is the length of the boundary line of an unperturbed flame front, as recorded by the Töpler method;
Δx	is the displacement of a point on the front along a standing wave;
h_0	is the amplitude of flame front fluctuations;
λ	is the length of waves forming on the flame surface;
ρ_1	is the density of a fresh reactant mixture;
ρ_2	is the density of reaction products.

LITERATURE CITED

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