ON THE MECHANISM OF FLAME ACCELERATION IN THE TRANSITION FROM NORMAL BURNING TO DETONATION

By

L. N. Pyatnitskiy

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It is known that the transition from slow burning to detonation in gaseous fuel mixtures occurs during the process of accelerated flame propagation. According to existing theories [1-3], in normal propagation of the flame from the closed end of the tube, the expansion of the combustion products causes motion in the fresh mixture ahead of the flame front. This leads to turbulence of the mixture, an increase in the flame surface due to nonuniformity of the distribution of the flow velocity over the cross section, and acceleration of the flame. Accelerating progressively, the burning creates an adiabatic-compression wave [4]. The latter, as the steepness of the flame front increases, produces a shock wave and then a detonation wave. Instead of dwelling on the phenomena which occur close to the place where the detonation arises, since these have been investigated in detail in a number of papers ([4-6] and others), let us turn our attention to the processes on which the mechanism of the flame acceleration is based.

An estimate shows [2] that in the transition from slow burning to detonation, beginning with normal flame propagation, the Reynold's numbers of the flow of fresh gas in front of the flame exceed its critical value by a factor of 5-10 or more. Therefore it is usually assumed [2, 7] that in the process of accelerated propagation the flame moves through a stabilized turbulent flow. This condition, however, is not fulfilled. The point is that the gas in front of the flame does not move along the entire tube, but only within the limits of the unsteady double gap [8] shown in the diagram in Fig. 1 (on the left). It consists of the shock wave, moving relative to the initial stationary mixture at a velocity D, and of the flame moving through the gas which is compressed by the wave and has a velocity w. The velocities of the shock wave and the flame are not the same, and therefore the distance between them l (the length of the gap) is constantly changing.

Let us consider the behavior of the gas in a cross section at a distance L from the ignition point after the advent of the shock wave. In the first instant after motion arises in the gas behind the wave, the gas velocity is constant over the cross section, but under the action of friction forces a flow-velocity profile corresponding to the given flow regime (Re number) begins to be established. The flame front advances into this cross section within a time $\tau = l/u_p$ (u_p is the propagation velocity of the flame relative to the walls of the tube). It is not difficult to establish that the time τ is less than the duration of the transition from normal burning to detonation, while the entire predetonation portion, as a rule, is less than the distance (40-50 diameters) at which the velocity profile is able to develop. This means that during the time τ the influence of the tube wall is not able to extend over the entire cross section, and the thickness of the boundary layer δ is small compared to the tube radius. Given this situation, the nature of the gas flow at the tube wall can be estimated on the basis of the solution to the problem of the formation of a boundary layer on a plate [9]. Then the states of the flow at the tube wall in the cross section L and at the end of a plate of length $x = w\tau$ are equivalent and depend upon the Reynold's number calculated for the plate length $\underline{x}$: $Re_x = wx/\nu$, or, correspondingly, for the analog of the plate length $(w\tau)$: $Re_{w\tau} = w(w\tau)/\nu$. With an accuracy sufficient for an estimate, the gas velocity in front of the flame may be replaced by the flame-propagation velocity, in the initial stage of the process and, accordingly, the equivalent plate length may be replaced by the length of the double gap l. Then the thicknesses of the laminar and turbulent boundary layers are described by the relations:

$$\delta_1 = 5{,}0\sqrt{\nu\tau} \approx 5{,}0\sqrt{\frac{\nu l_1}{w}} = 5{,}0\frac{\nu}{w}\sqrt{Re_l} \quad (1)$$

$$\delta_T = 0{,}37\,(w\tau)Re^{-1/5} \approx 0{,}37\,l_T\,Re_l^{-1/5}. \quad (2)$$

The transition from a laminar to a turbulent boundary layer occurs at $Re_1 \sim 5 \cdot 10^5 - 10^6$ and higher. From this we may estimate the critical values of the quantities l_1 and δ_1:

$$l_{1.cr} \approx \frac{\nu}{w}(5 \cdot 10^5 \div 10^6)\,^*; \quad \delta_{1.cr} \approx 5000\frac{\nu}{w}. \quad (3)$$

* When we speak of the motion of the gas within the limits of the double gap, where there are a large number of perturbations, it is natural to take the lower boundary of this interval and assume that $l_{1.cr} \approx 5.10^5\ \nu/w$.

As is known, the shape of the flame front depends upon how rapidly the burning is transmitted to the entire cross section from some one of its points which has a maximum rate of displacement relative to the tube wall. The velocity of this point (or zone) determines the flame-propagation velocity along the tube u_p. Let us call this point "the leading" point. In order to represent the structure of the flame in a certain cross section, it is necessary to analyze the state of the flow in it and to establish where the maximum value of u_p is located. The latter is equal to the sum of the velocity of the gas before the flame w and the velocity of the flame u_f relative to the gas. During laminar gas flow the flame moves through the gas at normal velocity $u_f = u_n$, and the position of the leading point is determined by the maximum value of w. In the general case, when the rms pulsation component of the velocity w' is not equal to zero, we may assume that in the first approximation $u_{p1} = w' + u_n$ and

$$u_p = w + w' + u_n \tag{4}$$

Then the position of the leading point is determined by the maximum value of the sum w + w'. For the case which interests us, when $\delta < R$, the distribution of w + w' over the cross section may be calculated with the aid of the data given in Ref. [10] for flow in a rectangular trough in the presence of an open boundary layer. The calculation shows that the maximum value of w + w' is found at a point of the cross section located close to the outer boundary of the turbulent boundary layer.

Let us now examine a typical accelerated flame-propagation pattern. A Töpler slit-scanning photograph of the process of flame propagation in a $CH_4 + 4O_2$ mixture in a tube 3 cm in diameter is shown in Fig. 1. The ignition point is located in the lower left corner of the picture. The flame trace is seen as a broad dark band. The slanted lines in front of the flame depict the motion of the shock waves in the double gap. The broken line corresponds to the velocity of sound in the given mixture. In its path the flame does not encounter shock waves which have been reflected from the opposite end of the tube, and in the course of propagation it assumes a number of natural intermediate shapes corresponding to the flow structure. After ignition and a short period of uniform motion there occurs an acceleration of the flame due to expansion of the reaction products and a corresponding increase in the surface of the flame front (Fig. 2a). As the mixture at the tube wall burns up, the flame fills the entire cross section, and its surface decreases. The deceleration stage begins. After a certain time a second acceleration of the flame begins, which is accompanied by the following phenomena. In a narrow zone at the tube wall pulsations arise, and shock waves, at first very weak (barely distinguishable in Fig. 2b) and then stronger (Fig. 2c), are formed. They move in front of the flame at an angle to the axis and, being reflected from the walls, create a spatially distributed system of pulsations of gas pressure and velocity. The chaotic velocity pulsations behind these waves give rise to a phenomenon, illustrated in Fig. 2c which is reminiscent of flame turbulence. With an increase in the length of the double gap the flame pulsations at the walls become more energetic, and finally this process leads to the appearance of stable leading points in the region of the walls (Fig. 2d). For one set of reasons or another one of them proves to be more stable, as a result of which a complete changeover in the shape of the flame front takes place (Fig. 2e). The process is progressive in nature. Moreover, as the length of the double gap increases, the distance Δ between the wall and the leading point increases.

The picture just given of this process may be explained with the aid of the above-mentioned assumption concerning the role of an open boundary layer in the formation of the leading point. Apparently, the origin of flame pulsations at the wall may be attributed to turbulence of the boundary layer, while the displacement of the leading points toward the center of the tube may be attributed to the development of the turbulence. Actually, at the moment of turbulence of the boundary layer the combustion rate in the narrow zone between the wall and the flame increases sharply. But since the length of the turbulent portion of the boundary layer is small at this moment, the turbulent mixture burns up rapidly, the flame speed in this zone decreases, and the shape of the flame front is restored. However, as the length of the double gap increases, the point at which the boundary layer becomes turbulent leaves the flame front behind, and the pulsations stop. At the place where the turbulent boundary layer intersects the flame front leading points are formed, which are displaced toward the center of the tube, as the boundary layer develops. The length of the double gap for which turbulence of the boundary layer occurs may be estimated from formulas (3). Assuming that the mean flame velocity over this portion is 200 m/sec and that the kinematic viscosity of the mixture $\nu = 0.2$ cm^2/sec, we obtain: $l_{1cr} \approx 5—10$ cm, $\delta_{1cr} \approx 0.5$ mm. As can be seen from Fig. 1, the length of the double gap attains this value in the cross section of the tube which is at a distance $L \approx 12$-22 cm from the place of ignition. Pulsations of the flame appear (Fig. 1 and Fig. 2b) at $L \approx 13$-16 cm. Thus we may assume that relation (3) well describes the conditions of the origination of turbulent boundary layer and flame pulsations at the walls of the tube. The results of the calculations of the thickness of the developed turbulent boundary layer and of the measurements of the distance Δ between the wall and the leading point for a number of cross sections are given in Table 1.

TABLE 1

L, см	l, см	$l_т = l - l_1$ см	δ, мм	Δ, мм	L, см	l, см	$l_т = l - l_1$ см	δ, мм	Δ, мм
25	12	7	1,7	1,5	36	20	15	3,2	3,1
26	12,5	7,5	1,8	2,0	45	25	20	3,9	4,0
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28	14	9	2,1	2,0	63	32	27	5,2	4,8
34	18	13	2,8	2,5	63	32	27	5,2	5,5
34	18	13	2,8	2,5					

In the calculations the gas velocity in the double gap is taken equal to 200 m/sec, its lower limit. However, the accuracy of the calculations of δ (cf. expression (2)) is practically independent of the velocity in the range over which the velocity can vary. The length of the laminar portion of the boundary layer was taken equal to 5 cm in accordance with a previous result. It is apparent from Table 1 that the computed values of the boundary-layer thickness describe the position of the leading point in the cross section of the tube with sufficient accuracy.

Consequently, the second acceleration of the flame is due to the origin and development of a turbulent boundary layer. It is precisely this circumstance which serves as one of the principal reasons for the appearance of gas pulsations and the increase in the combustion rate per unit of flame surface caused by these pulsations, and also the increase in the flame surface and the formation of relatively weak shock waves, which then accumulate into a shock wave capable of igniting the mixture.

Fig. 1. Diagram of double gap and Töpler slit-scanning photograph of the transition from slow burning to detonation.

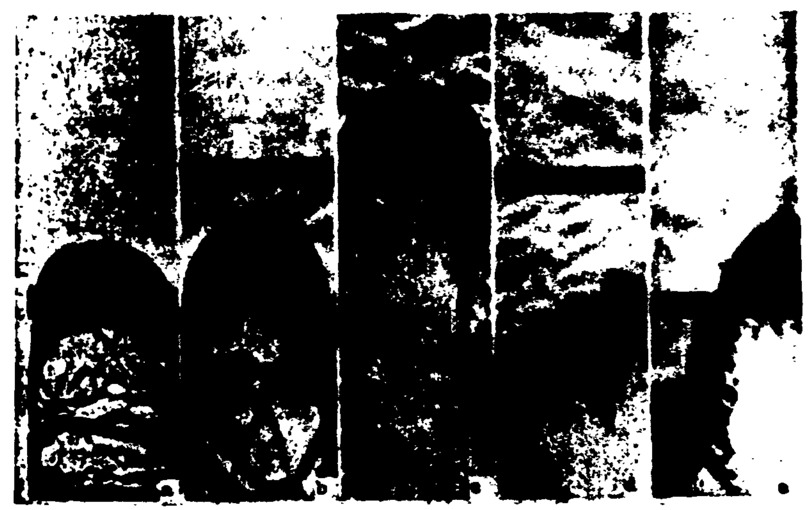

Fig. 2. Töpler photographs of a flame during the transition from slow burning to detonation in a tube of square cross section 28 X 28 mm^2. Exposure time 2 μsec. a) L = 4.6 cm; b) L = 14 cm; c) L = 16 cm; d) L = 31 cm; e) L = = 41 cm.

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FOREIGN TECHNOLOGY DIVISION

AIR FORCE SYSTEMS COMMAND

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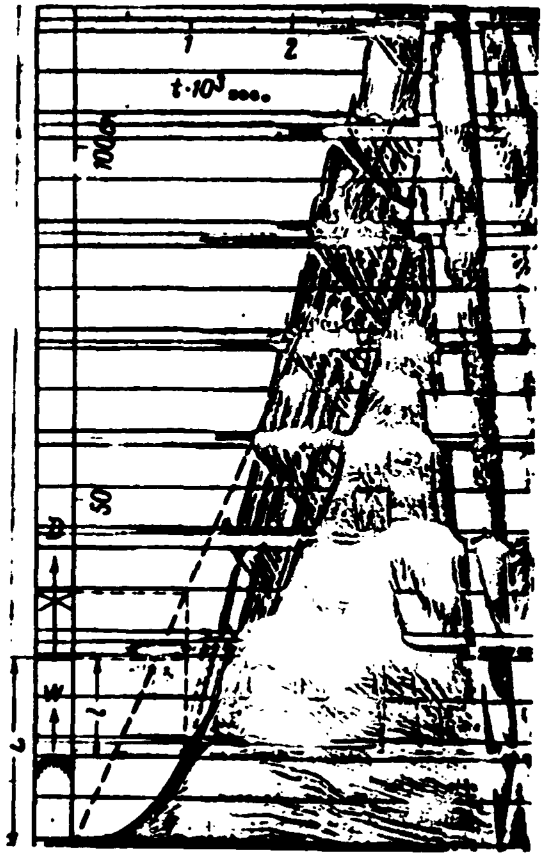

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