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Abstract

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

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It is known that the transition from slow combustion to detonation in combustible gaseous mixtures takes place in the course of accelerated flame propagation. According to existing views ($^{1-3}$), during normal propagation of a flame from the closed end of a tube, the expansion of the combustion products causes motion of the fresh mixture ahead of the flame front. This leads to its turbulization, to an increase in the flame surface due to the nonuniform distribution over the cross section of the flow velocity, and to flame acceleration. Progressively accelerating combustion creates an adiabatic compression wave (^{4}). As the steepness of the front increases, it gives rise to a shock wave and then to a detonation wave. Without dwelling on the phenomena occurring near the place where detonation arises, which have been examined in detail in a number of works ($^{4-6}$) and others, let us turn to the processes that underlie the mechanism of flame acceleration.

An estimate shows (^{2}) that, in the transition from slow combustion to detonation, beginning with normal flame propagation, the Reynolds numbers of the fresh-gas flow ahead of the flame exceed its critical value by 5-10 times or more. Therefore it is usually assumed (^{2,7}) that, in the process of accelerated propagation, the flame moves through a stabilized turbulent flow. Meanwhile, this condition is not satisfied. The point is that the gas ahead of the flame moves not along the entire tube, but only within the limits of a nonstationary double discontinuity (^{8}), shown schematically in Fig. 1 (left). It consists of a shock wave moving relative to the stationary initial mixture with velocity D, and a flame that moves through the gas compressed by the wave, which has velocity w. The velocities of the shock wave and of the flame are not the same; therefore the distance between them l (the length of the discontinuity) changes continuously.

Let us consider the behavior of the gas in a section located at a distance L from the ignition point after the arrival of the shock wave. At the first instant after the onset of motion of the gas behind the wave, its velocity is constant over the cross section, but under the action of frictional forces a flow-velocity profile corresponding to the given flow regime (Reynolds number) begins to become established. The flame front reaches this section after a time $\tau = l/u_p$ (u_p' is the velocity of flame propagation relative to the tube walls). It is easy to establish that τ is less than the duration of the transition from normal combustion to detonation, while the entire predetonation region, as a rule, is less than the distance (40–50 diameters) over which the velocity profile has time to develop. This means that during the time τ the influence of the tube wall does not have time to spread to the whole cross section, and the boundary-layer thickness δ is small compared with the tube radius. In this situation the character of the gas flow at the tube wall can be estimated on the basis of the solution of the problem of boundary-layer formation on a plate (^{9}). Then the state of the flow at the tube wall in the section L and at the end of a plate of length $x = w\tau$ is equivalent and depends on the Reynolds number, -

···for the plate length x: $\mathrm{Re}_x = wx/\nu$, or, respectively, for the analogue of the plate length $(w\tau)$: $\mathrm{Re}_{w\tau} = w(w\tau)/\nu$. In the initial stage of the process, the velocity of the gas ahead of the flame may, with sufficient accuracy for an estimate, be replaced by the flame-propagation velocity and, consequently, the equivalent plate length by the length of the double gap l. Then the thicknesses of the laminar and turbulent boundary layers are described by the relations:

$$\delta \ = 5.0\sqrt{\nu\tau} \simeq 5.0\sqrt{\frac{\nu l}{w}} = 5.0\frac{\nu}{w}\sqrt{\mathrm{Re}_l}, \tag{1}$$

$$\delta \ = 0.37(w\tau)\,\mathrm{Re}^{-1/5} \simeq 0.37\,l\ \mathrm{Re}_l^{-1/5}\,. \tag{2}$$

The transition from a laminar boundary layer to a turbulent one occurs at $\mathrm{Re}_l \sim 5\cdot 10^5 \div 10^6$ and higher. From this one can estimate the critical values of the quantities l and δ:

$$l_{.} \ \simeq \frac{\nu}{w}(5\cdot 10^5 \div 10^6)^*; \qquad \delta_{.} \ \simeq 5000\,\frac{\nu}{w}. \tag{3}$$

As is known, the shape of the flame front depends on how rapidly combustion from some point of it, having the maximum velocity of displacement relative to the tube wall, is transmitted to the entire cross section. The velocity of this point (or zone) also determines the velocity of flame propagation along the tube u_p. We shall call this point the "leading" point. In order to picture the structure of the flame in some cross section, it is necessary to analyze the state of the flow in it and to establish the location of the greatest value of the quantity u_p. It is composed of the velocity of the gas ahead of the flame w and the flame velocity u relative to the gas. For laminar gas flow the flame moves through it with the normal velocity $u \ = u$, and the position of the leading point is determined by the greatest value of the quantity w. In the general case, when the root-mean-square pulsational component of the velocity w' is not equal to zero, in a first approximation one may assume that $u \ = w' + u$ and

$$u_p = w + w' + u \, . \tag{4}$$

Then the position of the leading point is determined by the greatest value of the sum $w + w'$. For the case of interest to us, when $\delta < R$, the distribution of $w + w'$ over the cross section may be calculated using the data given in (10) for flow in a rectangular channel with an unclosed boundary layer. The calculation shows that the greatest value of $w + w'$ occurs at a point of the cross section located near the outer boundary of the turbulent boundary layer.

Let us now consider a typical picture of accelerated flame propagation. Figure 1 presents a Tepler photograph of a slit sweep of the process of flame propagation in a mixture of $CH_4 + 4O_2$ in a tube of diameter 3 cm. The ignition point is located in the lower left corner of the photograph. The flame trace is seen as a dark broad band. The inclined lines ahead of the flame depict the motion of shock waves in the double gap. The dotted line corresponds to the speed of sound in the given mixture. Along its path the flame does not encounter shock waves reflected from the opposite end of the tube, and in the course of propagation it assumes a number of natural intermediate forms corresponding to the structure of the flow. After ignition and a short period of uniform motion, flame acceleration occurs, associated with the expansion of the reaction products and, correspondingly, with an increase in the surface of the flame front (Fig. 2a). As the mixture burns out near the tube wall, the flame fills the entire cross section and its surface decreases. A stage of deceleration begins. After some time a second acceleration of the flame begins, which is accompanied by the following phenomena. In a narrow zone near the tube walls, flame pulsations arise with the formation of shock waves, at first very weak (in Fig. 2b they are barely distinguishable), then stronger (Fig. 2*b*). Ahead of the flame they move at an angle to the axis and, being reflected from the walls, create a system of spatial distribution of pressure pulsations and gas velocity. The chaotic velocity pulsations behind these waves produce a phenomenon resembling flame turbulization, which is illustrated in Fig. 2*c*. As the length of the double discontinuity increases, the flame pulsations at the walls become more energetic, and ultimately this process leads to the appearance of stable leading points in the near-wall region (Fig. 2*d*). One of them, for one reason or another, proves to be more stable, as a result of which a complete restructuring of the shape of the flame front occurs (Fig. 2*e*). The process is progressive in character. In this, as the length of the double discontinuity increases, the distance Δ between the wall and the leading point grows.

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* When the motion of gas within the double gap is being discussed, where there is a large number of disturbances, it is natural to take the lower boundary of this interval and to assume $l_{.} \simeq 5 \cdot 10^5 \, \nu / w$.

The picture of the process considered can be explained with the aid of the assumption stated above concerning the role of an unclosed boundary layer in the formation of a leading point. Apparently, the occurrence of flame pulsations at the wall may be attributed to turbulization of the boundary layer, and the displacement of the leading points toward the center of the tube—to its development. Indeed, at the moment of turbulization of the boundary layer in the narrow zone between the wall and the flame, the burning velocity increases sharply. But since the length of the turbulent section l_{t} of the boundary layer is small at this moment, the turbulized mixture burns out rapidly, the flame velocity in this zone decreases, and the shape of the flame front is restored. However, as the length of the double discontinuity increases, the point at which the boundary layer becomes turbulent overtakes the flame front, and the pulsations cease. At the point of intersection of the turbulent boundary layer with the flame front, leading points are formed which, as the boundary layer develops, shift toward the center of the tube. The length of the double discontinuity at which turbulization of the boundary layer occurs can be estimated from formulas (3). Assuming that the mean flame velocity in this section is 200 m/sec and the kinematic viscosity of the mixture is $\nu = 0.2$ cm^2/sec, we obtain: $l_{\text{l.cr}} \approx 5$–$10$ cm, $\delta_{\text{l.cr}} \approx 0.5$ mm. As is seen from Fig. 1, the length of the double discontinuity reaches such a value in a section of the tube located at a distance $L \simeq 12 \div 22$ cm from the ignition point. Flame pulsations, however, appear (Fig. 1 and Fig. 2*b*) at $L \simeq 13$–16 cm. Thus, it may be considered that relation (3) describes well the conditions for the occurrence of a turbulent boundary layer and of flame pulsations at the tube walls. The results of calculations of the thickness of the developed turbulent boundary layer and measurements of the distance Δ between the wall and the leading point for a number of sections are given in Table 1.

Table 1

L, cm	l, cm	$l_{\text{t}} = l - l_1$, cm	δ, mm	Δ, mm	L, cm	l, cm	$l_{\text{t}} = l - l_1$, cm	δ, mm	Δ, mm
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
28	14	9	2.1	2.0	55	29	24	4.7	5.4
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 discontinuity was taken equal to 200 m/sec—this is its lower limit. However, the accuracy of calculating δ (see expression (2)) within the limits in which the velocity may vary is practically independent of it. The length of the laminar section of the boundary layer, in accordance with the preceding result, was taken equal to 5 cm. From Table 1 it

Figure 1

Figure 1: Figure 1

Figure 2

Figure 2: Figure 2

is seen that the calculated values of the boundary-layer thickness describe, with sufficient accuracy, the position of the leading point in the tube sections.

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Fig. 1. Diagram of a double discontinuity and a schlieren photograph of a slit streak record of the transition from slow combustion to detonation

Fig. 2. Schlieren photographs of the flame during the transition from slow combustion to detonation in a tube of square cross section 28×28 mm^2. Exposure time 2 sec. a—$L = 4.6$ cm; b—$L = 14$ cm; v—$L = 16$ cm; g—$L = 31$ cm; d—$L = 41$ cm

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Consequently, the second acceleration of the flame is associated with the emergence and development of a turbulent boundary layer. It is precisely this circumstance that serves as one of the main causes of the appearance of gas pulsations and of the increase, caused by them, in the burning rate per unit surface of the flame, as well as of the increase in its surface and the formation of relatively weak shock waves, which then cumulate into a shock wave capable of igniting the mixture.

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