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TRANSFORMATION OF SLOW BURNING INTO DETONATION

-USSR-

By
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ON THE TRANSFORMATION OF SLOW BURNING INTO DETONATION

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/Following is a translation of the article entitled "O perekhode medlennogo goreniya v detonatsiyu" (English version above) by K. I. Shchelkin in <u>Zhurnal Eksperimental'noy i Teoreticheskoy Fiziki</u> (Journal of Experimental and Theoretical Physics), Vol 24, No 5, Moscow, May 1953, pages 589-600./

This present paper deals with the elementary theory of transformation of slow burning into detonation in tubes. It is shown in this paper that the basic cause of pre-detonational acceleration of buring in tubes lies in the effect of the movement of unburned gas on the burning, and, first of all, the effect of the turbulence of this gas upon the velocity of the flame.

Introduction

Certain considerations about the mechanism of the pre-detonational acceleration of theme have been recently published (1). These considerations were subjected to justifiable criticism (2), with which we can only join. At the same time it must be admitted that the mechanism of acceleration due to the turbulence of gas against which several arguments had been presented in the above-mentioned study (1), and, in general, the problem of the transformation of slow burning into detonation in tubes is not treated in any detail anywhere, while certain details of this process have not been discussed at all. Such a situation leads, as practical expwrience shows, to misunderstandings. In connection with this, an attempt is being made later in this paper to present a brief treatment of the fundamentals of the elementary theory of transformation of slow burning into detonation into tubes.

The Basic Kinds of the Propagation of Burning in Gas Mixtures

There are two basic methods of the propagation of flame in gas mixtures: the passage of combustion from layer to layer due to heat conductivity and diffusion, and the propagation of combustion from layer to layer owing to compression in the impact wave (detonational propagation of combustion).

The passage of combustion by menns of heat conductivity and diffusion is realized in extremely varied and, at first glance, completely different flames. The flat flame in the gas at rest, i.e., the flame whose radius of curvature is many times greater than the width of the burning zone, propagates in air-containing mixtures of common burning gases (natural gas, methane, gasoline fumes, etc.) at a velocity of several tens of centimeters per second. An exception is found in air mixtures of hydrogen, in which the velocity of propagation is considerably greater than that in other mixtures; in the former mixtures the velocity reaches 2.7 m/sec. Flame velocities in oxygen mixtures, due to high temperatures which develop in the course of burning, and due to higher velocities of the chemical reactions of combustion, is considerably higher than in air mixtures of the same fuels and reach 10-12 m/sec.

The velocity of the propagation of the flat front of the flame in relation to the immobile gas, which was mentioned earlier, is called the normal flame velocity. The normal flame velocity has the character of a physico-chemical constant of the mixture. It increases with the absolute temperature of the initial mixture, depends on its composition, and changes as the initial pressure varies. However, all factors which increase the normal velocity can increase the speed of flame propagation only insignificantly in comparison with that effect which may be exerted upon the velocity of the propagation of burning by conditions of the movement of the unburned gas.

The gist of the matter is that usually the velocity of flame propagation exceeds the normal velocity of the flame. For example, in tubes, owing to the irregular distribution of velocities of the unburned gas in front of the flame along the radius of the tube, or due to the turbulence of the unburned gas, or even because of the formation of convection currents, the flame at individual sectors of the tube cross-section is attracted forward by volumes of gas possessing the highest velocities. The surface area of burning increases as a result of this and the total amount of gas is increased in the process, i. e., the amount of gas un-ned in one unit of time. The velocity of the flame propagation thus begins to become determined not only by the normal velocity of the flame, but also by the advanced generation of focal points of burning forward, and by the velocity of the penetration of unburned gas by those focal points of burning (3).

Convection currents, turbulence, jets of gas, and whirlwinds, especially created in the volume of combustion, can accelerate the combustion by tens and hundreds of times, and increase the velocity of the propagation of flame. It must be borne in mind that combustion is accompanied by the radiation of great quantities of heat, which calls forth an expansion of the burning gases and a shifting of the masses of unburned gas. Therefore, in the process of burning, especially in non-structured conditions (outside the conditions of furnaces) there often proves essential not that movement of gas which had existed at the beginning, prior to the moment at which the mixture was ignited, but those movements which come into existence in the process of, and as a result of burning. Cases are known, when due to the movement of gases, which movement is generated in particular in a process of combustion, the velocity of the propagation of the flames reached many tens and even many hundreds of meters per second (4).

In all cases burning in the moving environment is transmitted from the burned gas to the unburned, just as in a medium at rest, by processes of heat conductivity and diffusion, i. e., relatively slow processes, with a velocity equal to the normal selocity of the flame. But the increase in the velocity of the propagation of burning in the moving gas takes place due to the phenomenon, pointed out earlier, of the advanced forward springing into existence of focal points of burning by means of currents, turbulence, etc., with a great velocity, which focal points ignite unburned gas, thus increasing the surface area of burning.

Certain significance may lie also in the increase of heat conductivity and diffusion due to turbulence if the scope of turbulence is smaller than, or comparable to, the width of the zone of normal burning, which amounts to fractions of a millimeter at normal pressure and for usual mixtures. In that case, as a result of movement of gas, the normal velocity of the movement of flame increases. It follows from all that has been said so far, that we may not examine the process of flame propagation outside of realistic conditions in which it takes place, and particularly, we may not examine it divorced from the conditions of the movement of unburned gas, which originates in the course of burning.

Detonational burning in smooth tubes propagates with a fully definite constant velocity in each gas mixture; the size of this velocity for different gas mixtures lies within limits of 1.7 to 3.5 km/sec and can be computed from formulas of the gasodynamic theory of detonation.

We must mention two forms of detonational combustion in tubes which are distinctive in their mechanism of the propagation of burning: "spinal" detonation and detonation in tubes with coarse inner surfaces. In the former, as well as in some cases of the latter, the ignition of the gas mixtures occurs on a relatively small surface and not across the whole cross-section of the tube, as happens in the case of a common detonation. In the case of the spinal detonation, the ignition of gas occurs at the oblique rapid change of compression -- at the break-point of the impact wave (5), while in the case of a detonation in coarse-surfaced tubes, in places where the wave impacts against the point of coarseness (6). The burning-up of the remaining gas in both cases proceeds comparatively slowly (in the turbulent wake) over one or two and, possibly, more diameters of the tube.

Despite a certain difference in their method of propagation, all forms of detonation do not substantially differ from each other with regard to their formation. For the formation of a detonation of any type the existence of a powerful disruption, of a strong impact wave, is necessary.

A powerful impact wave, and consequently, the detonational burning as well may, in certain cases, come into existence as a result of acceleration of slow burning. The task of the theory of transformation of slow burning into detonation, to which, in particular, this present work is devoted, lies in the discovery of causes which determine the transformation of slow burning, which propagates at the velocity of several meters per second, into detonation; in other words, the discovery of causes which bring about as a result of combustion the creation of an impact wave which ignites the gas mixture and effects the detonation.

The Formation of an Impact Wave in the Tube

In order to have a detonation appear, it is necessary, as may be concluded from the preceding section, first of all to have formed an impact wave capable of igniting the gas through shock-compression. Usually this requires a temperature in the front of the wave equal to several hundreds of degrees, and a pressure of 10-20 kgm/cm^2. Since we are concerned now with the transformation of slow burning into detonation, and not with the detonation, which comes into existence under the influences of strong impulses, e.g., from the effect of the explosion of a charge of an explosive substance, we must turn to the general case of the appearance of the impact wave under the influence of slow processes.

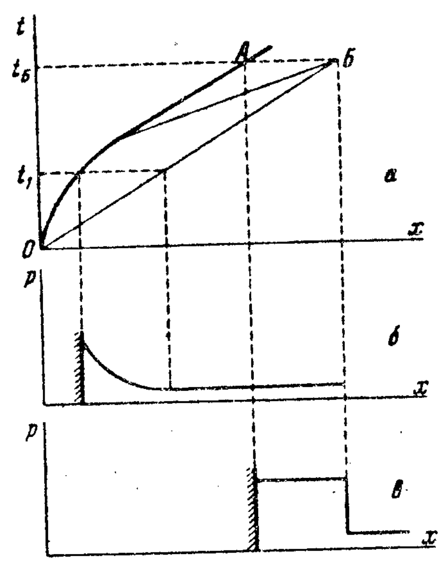

Figure 1 [Right-hand column of letters read, top to bottom, B,a,x,d,x,v,x.)

Gasodynamics tells us that if the piston moves with an acceleration inside a tube at a subsonic velocity and the velocity of the piston increases gradually, then in front of the piston there may occur a disruption of the continuity of pressure, temperature, density, and velocity of gas. At the point of disruption originates the impact wave which expands in the direction of the movement of the piston. In figure 1 at a in the surface x-t (path-time) there is presented the accelerated movement of the piston (line O-A). The problem of the movement of gas in front of the piston is solved by the method of characteristics.. Disruption occurs at point B; from here there originates the impact wave in which the pressure is lower than at the point of the origin of disruption and in the cross-sections situated closer to the piston, but the temperature of the impact wave is higher. The parameter of the impact wave may be easily computed for the case of deliberate disruption (7).

In figure 1 b and v schematically represent the distribution of pressures at moments t_1 and t_B. At the moment t_B there is formed a disruption in the continuity of conditions and velocities. The gradual shifting of pressure transforms itself into an abrupt shifting, because the compression in each cross-section of the tube expands at an ever higher velocity, proportional to the proximity to the piston. This depends, on the one hand, on the fact that the speed of sound at which compression without impact propagates is higher the more the gas is compressed, and consequently, the more it is heated; and on the other hand, this depends on the fact that the velocity of the movmment of the gas through which the compression expands increases with the degree of proximity to the piston. As a consequence of those causes which have been pointed out, from the gradual shifting of pressure there originates the disruption, and from the disruption -- the impact wave.

All characteristics which deviate from the line representing the movement of the piston converge in one point only if one, fully definite, form of this line is at hand. Consequently, the elementary waves of compression, receding from the accelerating piston, will overtake each other and will blend themselves into a disruption in one cross-section (as is shown in figure 1, v) only in the case of a definite distribution of pressure in front of the piston (7). In the general case, at an arbitrary distribution of pressure, the elementary waves will converge not in one cross-section of the tube but over a certain length of it. Figure 2 represents one of the cases of the unifying of the compression waves over a certain length of the tube. The first more or less powerful disruption occurs at point 1. At this point the impact wave is formed; the velocity of the disturbance, which propagates through the gas at rest, increases. In the sector 1-2, called the circumvention of characteristics, the initial wave

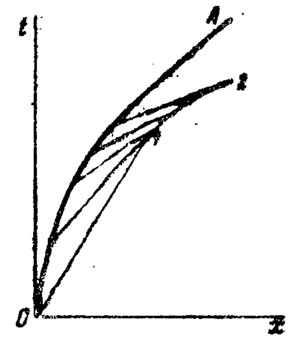

Figure 2

of impact is overtaken by the following waves of compression, and it velocity gradually increases. Instances of another type of a gradual enhancing of the disruption are possible also; they are represented by the circumvention of characteristics of other kinds.

Earlier we have talked about the moveeent of gas in front of the accelerating piston. In the case of the movement of the piston at a constant velocity, gas in front of the piston will move at the same constant velocity. It is easy to determine the pressure of the moving and compressed gas by taking advantage of the equations of the conservation of mass and of motion written for the case represented in figure 3:

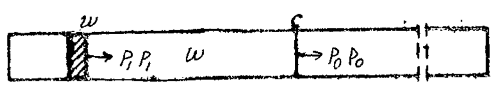

Figure 3

$$(c-w)\,{}_1 = \rho_0 c; \qquad (1)$$

$$(c-w)\,{}_1 w = p_1 - p_0 , \qquad (2)$$

where c is the velocity of the expansion of the disturbance front (for weak waves this is the speed of sound), w is the velocity of gas movement in front of the flame, p_1 and p_0 are the pressures of compressed and non-compressed gas, ρ_1 and ρ_0 are the corresponding densities.

From equations (1) and (2) it follows that

$$p_1 - p_0 = \rho_0 c w \qquad (3)$$

the pressure depends linearly on the velocity of the gas movement. Constant pressure corresponds to a constant velocity. To obtain a higher pressure, a higher velocity of gas, and consequently, of the piston is needed.

It is clear from all that has been said above that for the formation of a more or less powerful impact wave at low (below the speed of sound) velocities of the piston movement, it is necessary for the piston to move under acceleration.

The Impact Wave in Front of the Flame

Let us assume that the flame is expanding in an infinitely long tube, which is closed on one side, from the closed end in the direction of the open end (figure 4).

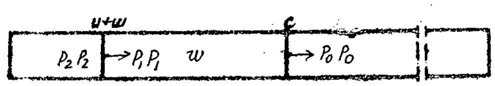

Figure 4

In order to determine the pressure in front of the flame, we may, in the same manner as earlier in the case of the piston, make use of the equations of the conservation of mass and of motion:

$$[c - (u + w)]\rho_1 + (u + w)\rho_2 = c_0 \,, \qquad (4)$$

$$[c - (u + w)]\rho_1 w = p_2 - p_0 \,, \qquad (5)$$

where u is the flame velocity in relation to the unburned gas, p_2 is the pressure, and ρ_2 is the density of burned gas.

From equations (4) and (5) we at once obtain the expression for pressure, the form of which depends on neither the equations of the states of the burned and the unburned gases, nor on the quantity of energy given off in burning:

$$p_2 - p_1 = \rho_0 wc - \rho_2(u + w)w. \qquad (6)$$

In that case, when flame velocity and gas velocity in front of the flame are small compared to the speed of sound we may ignore the second term of the right-hand part of expression (6). Neglecting the second term, generally speaking, is acceptable even if u + w is quantiatiively comparable to the speed of sound, because the density of the burned gas ρ_2 is almost one order smaller than the density of the unburned and undisturbed gas ρ_0;

The pressure of the burned gas p_2 can be regarded, with sufficient exactness, as equal to the pressure of gas p_1 moving with the velocity w. Expression (6), in which we have ignored the second term of the right-hand part and have equated p_2 and p_1, is transformed into the inter-relationship (3) obtained for the pressure in front of the piston moving with the speed of w,

$$p_2 - p_0 \approx p_1 - p_0 = \rho_0 c w . \qquad (3a)$$

The flame moving at the velocity of u + w, relative to the walls of the tube, creates ahead of its front the same pressure as that created by the piston moving at the velocity w. To create an equal pressure, the flame velocity relative to the walls of the tube must be higher compared to the piston velocity, in view of the fact that the flame may be likened to the piston which allows to pass through and leaves behind a certain amount of gas which is determined by density ρ_2 and by the distance covered from the closed end of the tube.

Because only one, fully definite, velocity of the current, w, can correspond to the definite flame velocity, each value of the flame velocity has only one corresponding definite value of pressure. From this it follows that we cannot obtain a gradual increase of pressure in front of the flame front without changing the velocity of the flame relative to the gas, u, and not changing the gas velocity, w, in so doing. Because of this we must necessarily have an acceleration of the flame relative to the unburned gas, in order to obtain a gradual increase of pressure in front of the flame front. In the absence of such an acceleration, the transformation of slow burning into detonation is impossible. The task, consequently, consists of the need to find the causes and conditions of the existence of flame acceleration.

The Basic Cause of the Pre-detonational Acceleration of Slow Burning in Tubes

It was pointed out above that burning cannot be examined when separated from the conditions of movement of unburned gas, because the movement of the unburned gas represents practically the most potent factor that is capable of accelerating the burning. Let us examine from this viewpoint the movement of gas in front of the flame in the long tube in cases of ignition of the gas mixture at the closed end of the tube. An overwhelming portion of experimental material belongs to this simple case.

It was shown earlier (8) that in all cases without exception when burning is transformed to detonation, the dimensionless inter-relationship (similar to the Reynolds' number Re), consisting of the normal flame velocity u_H, the diamterr of the tube D, and the kinematic viscosity of the mixture ν, exceeds the critical value characteristic for the transformation of the laminar flow into a turbulent one:

$$Re = u_H D/\nu > Re_{cr} . \qquad (7)$$

In the borderline cases of the transformation of slow burning into detonation, this number -- in terms of the mixture composition and in terms of the pressure -- is equal to the critical value, and in cases of those compounds and pressures, at which detonation does not take place, it is below the critical. Using the rule presented above, it was possible to compute the values of the limits of the transformation of slow burning into detonation.

In the study (8) it was pointed out that in computations of this sort one should use not the flame velocity, but the velocity of the gas at the front of the latter, and it was noted, that when the flame velocity is substituted for the velocity of the gas, an error is made; however, its order of magnitude was pointed out erroneously and no precise figures were presented. In general the problem of the limits of the transformation of slow burning into detonation had not been analyzed to completion. Later, Zel'dovich (9) computed the size of the error in the definition of the Reynolds' numbers.

It may be assumed (on the basis of the law of the conservation of matter), that in instances of ignition at the closed end of the tube the velocity of the movement of unburned gas is related to the flame velocity:

$$w = C(\pi - 1)u_H , \qquad (8)$$

where π is the relation between the volumes of gas after and before the burning (for small velocities of the flame, $= Tn/T_o n_o$; here T_o , n_o , and T, n are the temperature and the number of moles before and after the burning), and C is the multiplier, which accounts for the effect of irregular distribution of velocities in the tube along the radius on the velocity of propagation of the flame, which multiplier is equal to the ratio of the surface area, which circumscribes the flame front, to the cross-section area of the tube.

If in computing the Reynolds' number, we do not use the normal flame velocity, u_H, but the velocity of gas, w, then all of the Reynolds numbers, discussed above, will increase by five to fifteen times, and the basic postulate, expressed in the study (8), that in the transformation of slow burning into detonation the Reynolds' numbers of the gas stream in front of the f flame always exceed the critical volume, will become even more convincing. Along the borderlines of the transformation of slow burning into detonation, the numbers will not be equal to the critical volume, as was the case in the computations when, in the expression for the Reynolds' numbers, the normal flame velocity is substituted for the velocity of the gas, but the former numbers will also exceed the critical value by five to ten times. In the result, without touching upon the problem of the limits of the transformation of slow burning into detonation, the basic deduction may be made that in the transformation of slow burning into detonation the stream of unburned gas, on which the accelerating flame propagates, must always and unavoidably become turbulent. It is amazing that certain authors (9,10), while mentioning the error in the computation of the Reynolds' numbers in regard to the arguments against the mechanism of transformation of slow burning into detonation, which has the principal role in this process of turbulence, do not mention the fact that a correction of the error in the computation of the Reynolds' numbers of the gas stream in front of the flame does not lead to a weakening, but rather to a strengthening of the status of the theory of pre-detonational acceleration of burning, against which they argue.

Thus, the stream of unburned gas in front of the flame cannot but become turbulent, and having become turbulent, it cannot fail to accelerate burning. The acceleration of burning, in its own turn, increases the velocity of the stream and, consequently, the extent of the turbulent pulsations of the velocity, which will lead -- when the length of the tube is sufficient -- to a new gradual increase of velocity in the flame, as a result of which the burning will acquire self-acceleration.

The fact that the Reynolds' numbers of the stream of unburned gas in front of the flame exceed the critical value does not stand as the only fact which proves that turbulence plays an important role in the pre-detonational acceleration of burning. Another quite important demonstrative fact, which points to a decisive action of turbulence in the process of the acceleration of burning, lies in the effect of the coarseness upon the pre-detonational acceleration of the flame, since coarseness always enhances the degree of turbulence of gas in the tube.

If we glue a layer of sand unto the inner surface of a smooth tube, thus making it coarse, or if we create coarseness inside the tube by any other means, then the detonation in the tube comes about more easily than in a smooth tube. The point of origin of the detonation comes closer to the point of ignition when this is done; the limits of the transformation of slow burning into detonation are extended in terms of pressure and composition of the mixture. The coarseness represents the most potent way of acting upon the transformation of slow burning into detonation (11).

No other methods succeeds in bringing the point of origin of the detonation in the tube to the point of the ignition of the mixture as much as this can be accomplished by means of the coarseness of the tube walls, in a gas mixture with a given composition. The effect of coarseness cannot be explained from any other viewpoint that differs from the viewpoint which ascribes the principal role in the acceleration of burning to aerodynamic factors and, first of all, to turbulence. Granted that the opponents of such a formulation of the problem contend that coarseness brings the point of origin of the detonation nearer to the point of ignition as a consequence of the fact that the relatively weak wave of impact of front of the flame is increased when it is repelled from coarseness, and the gas in it ignites itself more easily than in a wave where not repelling takes place. Thus fully just contention posseses validity only in cases where the flame has already been sufficiently accelerated and when a sufficiently powerful wave of compression has already come into existence, i. e., when the impact wave already exists but the temperature therein is not yet sufficient for the gas to ignite. Indeed, in such cases, any obstacle which brings about a local repelling of the wave, brings closer the point of origin of the detonation to the point of ignition. Thus, the long-known considerations concerned with the role of the repulsion of the impact wave from obstacles in the process of the formation of the detonation must be taken into consideration in the examination of the last stage of the process of the formation of the detonation; but these considerations cannot be regarded as serious arguments opposed to the mechanism of the acceleration of burning, which mechanism ascribes the principal role in the acceleration of burning,to the turbulence of gas in front of the flame, because these arguments do not have any relation to it at all. This becomes particularily clear if we remember that flames in coarse tubes accelerate up to hundreds of meters per second even in gas mixtures incapable of detonating (4), i.e., in such mixtures which are not ignited by compression in the wave of impact and for which the contention that in coarse tubes the detonation occurs closer to the point of ignition due to the repulsion of the impact wave from the coarseness, does not have any meaning at all.

In the light of all that has been said so far it is clear that the question of the accelerating effect of the movement of gas and, more precisely, of turbulence upon burning in the pre-detonational burning cannot occasion doubts. From the fact that the unburned gas in front of the slow-burning front, in the transformatinn into detonation, is always more turbulent, as well as from the fact that the coarseness of the tube walls, as pointed out above, exerts the most powerful accelerating influence upon the origin of the detonation and upon the acceleration of the burning in general, we may deduce that the aerodynamic aactors are the most decisive ones in the process of the transformation of slow burning into detonation. However, for a final judgment of the mechanism of acceleration, it is necessary to examine, from the aerodynamic viewpoint, the basic regularities of this process and to compare the conclusions with the experimental material.

Determination of the Distance between the Point of Ignition and the Point of Origin of the Detonation

The distance between the point of ignition and the point of origin of the detonation may be evaluated approximately for cases of ignition of the gas mixture at the closed end of the tube, as being the distance within which the wave of impact in front of the piston is formed; the piston accelerates in confirmity with the same law which in reality governs the acceleration of the flame. Because at equal velocities of the piston and the flame, the velocity of the gas movement in front of the flame, is higher than the gas velocity in front of the flame, the distance from the point of ignition to the point of origin of the detonation, as determined in the above-noted approximation, will be much shorter than in reality. However, in view of the fact that the distance from the point of ignition to the point of origin of the detonation is determined below with an exactness up to the precision of the constant multiplier, this deviation is not substantial.

In the general case, the impact wave in front of the accelerating piston, having formed itself in the cross-section of the tube corresponding to point 1 in the area x-t (figure 2), gradually becomes stronger along the path between point 1 add point 2 through the waves of compression, which depart from the accelerating piston and overtake the disruption front. The strengthening of the wave in the area x-t is expressed by the change in the slope of line 1-2 in figure 2, which represents the circumvention of characteristics that depart from line OA, which depicts the path of the piston. Generally speaking, the temperature and the pressure in the impact wave, formed from the disruption at point 1 in the area x-t, may prove insufficient for the initiation of the detonation of the gas mixture, and detonational ignition will occur only after the strengthening of the impact wave, i.e., somewhere on the line 1-2 in the same area (figure 2). However, it is further assumed, for the sake of simplicity, that the detonation occurs as soon as the disruption occurs, i.e., at point 1 in the area x-t.

The position of point 1 (figure 2) is determined by coordinates x_1 and t_1:

$$x_1 \sim c_o^2 / \ddot{x}(0), \qquad (9)$$

$$t \sim c_o / \ddot{x}(0), \qquad (10)$$

where c_o is the speed of sound in unexcited gas, $\ddot{x}(0)$ is the acceleration of the piston at the beginning of its movement (12). The acceleration of the piston $\ddot{x}(0)$, equal to an accepted approximation to the acceleration of the flame at the beginning of the propagation, will be determined by the law of dependence of the flame velocity on the velocity of the movement of gas. The dependence of the flame velocity on the velocity of the movement of gas in front of the flame, w, may be represented by means of the relationship (3):

$$u_H = Cu_H\sqrt{1 + (Bv^2 + u_H^2)} = Cu_H\sqrt{1 + (Bk^2w^2/u_H^2)}, \quad (11)$$

where B is the constant multiplier of the order of unity, v is the median quadratic velocity of turbulent pulsations, u_H is the normal flame velocity, C is the coefficient which takes into account the increase in t the flame surface due to the irregular distribution of velocities of the stream along the diameter of the tube, k is the degree of turbulence, equal to k = v/w.

The inter-relationship (11), in the case of weak turbulence ($v \ll u_H$) takes on the form:

$$u_P \sim Cu_H\cdot(1 + B'k^2w^2/u_H^2) . \quad (12)$$

For strong turbulence, ($v \gg u_H$), ignoring the number one under the radical (11), it may be supposed

$$u_P \sim Cv. \quad (13)$$

In determining the acceleration of the flame it must be considered that from the moment of the appearance of the velocity, w, to the moment of gradual increase of the flame velocity under the influence of the turbulization of the stream, which has the velocity of w, there elapses a time equal to the time necessary for the propagation of the turbulence from the walls of the tube out to all of its cross-sections. This time is proportional to

$$D/v, \quad (14)$$

where D is the diameter of the tube.

Taking into account (12), (13), and (14) we shall get an acceleration of the flame for cases of weak turbulence

$$\ddot{x}(0) \sim \frac{Cu_H(1 + B'k^2w_0^2/u_H^2) - Cu_H}{D/v} \sim \frac{Ck^3w_0^3}{Du_H}; \quad (15)$$

and for cases of strong turbulence

$$\ddot{x}(0) \sim Ck^2w_0^2/D, \quad (16)$$

where w_o is the velocity of the unburned gas at the beginning of the acceleration of burning.

The distance from the closed end of the tube, where the ignition of the gas mixture occurs, to the point of origin of the detonation, considering that $w_o = C(\pi - 1)u_H$, proves to be proportional

$$x_1 \sim c_o^2 D / C^4 k^3 (\pi - 1)^3 u_H^2 \quad \text{-- weak turbulence} \tag{17}$$

$$x_1 \sim c_o^2 D / C^3 k^2 (\pi - 1)^2 u_H^2 \quad \text{-- strong turbulence.} \tag{18}$$

The greatest amount of material on the study of the transformation of slow burning into detonation deals with the case, which is intermediate between the extreme cases of weak and strong turbulence examined above. Indeed, if we consider that $v = kw$ and $w_o = Cu_H(\pi - 1)$, then the condition $v \gtrsim u_H$ becomes transformed into

$$kC(\pi - 1) \gtrsim 1 . \tag{19}$$

Bearing in mind that for smooth tubes $k \sim 0.05$, for the coarse tubes $k \sim 0.1$, and π for oxygen mixtures, for which experimental studies are available, is of the order of 7-8 and $C \sim 2$-3, we shall get

$$0.6 \lesssim kC(\pi - 1) \lesssim 2 ,$$

i.e., the resultant kC (- 1) does not differ much from one and, consequently, v does not differ much from u_H. The distance from the point of ignition to the point of origin of the detonation must therefore be considered proportional to

$$x_1 \sim c_o^2 D / C^n k^m (\pi - 1)^m u_H^2 , \tag{20}$$

where n is of the order of 3-4 and m is between 2 and 3.

From the inter-relationship (20) and in agreement with experiment it follows that the distance from the point of ignition to the point of the origin of the detonation is proportional to the tube diameter and increases as the speed of sound increases. The distance x_1 decreases as the normal flame velocity increases, as is well-known from experiment. In qualitative agreement with experiment it is very considerably shortened as the degree of turbulence of the gas stream increases (with the increase in coarseness of the tube). Finally, the quantity x_1 decreases as the ratio of the volume of the products of burning to the initial volume of the mixture increases (with the increase in π).

Formula (20) points to a strong dependence of the distance between the point of ignition and the point of origin of the detonation on the coefficient C, which dependence takes into account the increase in the flame velocity under the effect of irregular distribution of the gas velocities in front of the flame along the corrs-section of the tube. In smooth and coarse tubes the coefficient varies little in the process of the pre-detonational acceleration of burning; it does not increase and therefore, the distribution of velocities represents not the principal but a secondary factor determining the acceleration of the flame. However, special cases are possible, in which the mechanism proposed by Zel'dovich is realized and in which the changes in the coefficient C, and consequently, the effect of the distribution of velocities on the velocities of burning, can become determining factors in the process of the formation of the detonation. The quantity C can be sharply increased by placing diaphragms at the beginning of the tube, through the openings of which the flame escapes far ahead, igniting great masses of gas add strongly increasing the surface, and, consequently, the velocity of burning. The powerful effect of the diaphragms on the acceleration of burning in tubes is well-known. The point of the origin of the detonation can be brought sharply closer to the point of ignition by placing it the beginning of the tube a "detonational case", i.e., a volume with partitions, which almost completely overlaps the cross-section of the volume and increases the path of the flame in it. Burning is accelerated in the detonational case also to a considerable degree due to the great irregularity in the distribution of velocities.

As follows from the facts described earlier the inter-relationship (20) well describes a large part of the experiments. Its shortcoming lies in that it does not provide in manifest form the dependence of quantity x_1 on the initial pressure of the gas mixture. The experimental findings show that in a certain region of pressures the distance x_1 contracts as pressure is increased to a certain limit, after which the action of pressure is either weakened or ceases altogether. It was earlier shown (8) that in the area where pressure acts on the transformation of slow burning into detonation, the pre-detonational burning accelerates as the pressure is increased. This acceleration cannot be explained by the dependence of normal velocity on pressure, which gives a reverse effect. It remains to be assumed that the increase of initial pressure within certain limits increases the turbulence of the mixture. The increase, within certain limits, of the Reynolds' numbers of the gas stream in front of the accelerating flame may, in the non-stationary case under discussion, strongly facilitate the development of the turbulence.

It is interesting to note one peculiarity in the process of the formation of the detonation, which is easily explained from the viewpoint of the mechanism described of the transformation of slow burning to detonation. In the majority of cases of the appearance of a detonation, the ratio of the distance from the closed end of the tube, where the ignition of gas occurs up to the point of the detonation divided by the time elapsed from the moment of ignition to the moment of the origin of the detonation is equal precisely to the speed of sound in the unexcited gas mixture. From figure 2 it follows, obviously, that if the detonation originates at point 1 in area x-t (figure 2), where the circumvention of characteristics 1-2 begins, then the mentioned relationship $x_1 \div t_1$ is exactly equal to the speed of sound because point 1 is situated on the first characteristic, $x = c_o t$, which goes through the beginning of the coordinates. In that case, when the detonation originates not at point 1, but somewhere on the line 1-2 between points 1 and 2, then the ratio of the distance from the point of ignition up to the point of the origin of the detonation divided by the time elapsed from ignition up to the moment of the origin of the detonation will exceed the speed of sound, c_o. In this case, it is useful to take into account that the origin of the detonation between points 1 and 2 points to the fact that the temperature add the pressure of the wave, which originates at point 1 in the area x-t, are insufficient for the detonational ignition of the gas.

Not excluded are cases when the ratio of the distance from the point of ignition up to the point of the start of the detonation divided by the time elapsed from the moment of ignition up to the moment of the origin of the detonation, will be lower than the speed of sound, c_o, but this always testifies to the fact that the acceleration of the flame, which had effected the appearance of the disruption and of the impact wave, and had led to the formation of the detonation, began not immediately after the ignition of the mixture, but only after some time, in the course of which the flame was moving without acceleration.

In conclusion, let us examine three additional possible cases of the transformation of slow burning into detonation.

a) The transformation of slow burning into detonation when the mixture is ignited at the open ofd of the tube. The first researchers into the detonation had established that when ignition is made at the open end of the tube, the flame initially moves at a constant and comparatively low velocity, then the flame begins to vibrate and, finally, sufficiently far inside the tube it accelerates and passes into detonation. If we place a wire spiral at the open end of the tube, a spiral which creates resistance to the stream of products of burning flowing from the tube, then the acceleration of burning occurs on a smaller path, and the stage of vibrational burning is absent. From the mere description of these facts it becomes clear that the acceleration of burning, when ignition occurs at the open end of the tube, comes about only when the unburned gas in front of the flame picks up motion and acquires velocity inside the tube in the direction from the open to the closed end. As long as the products of burning are freely flowing out through the open end of the tube, no acceleration occurs. Hampering the flow of the products of burning by the spiral as they leave the tube facilitates the acceleration of burning, because it accelerates the movement of the unburned gas.

b) The origin of the detonation in a short tube. When gas is ignited at the closed end of the short tube, the length of which is comparable to the length of the pre-detonational path of the flame, a substantial role is played by the repulsion of the waves of compression from the closed end of the tube, which is opposite to the point of ignition (figure 5).

9 8 7 6 5 4 3 2 1

Figure 5

In the short tube, as a result of the repulsion mentioned, the detonation can originate closer to the point of ignition than in the case of a long tube, other conditions being equal. Sometimes igntion occurs, when the wave is repulsed from the end of the tube, at a fairly considerable distance ahead of the front of the expanding flame. It is clearly seen from the last example that the origin of the detonation at the very end of the tube, where there is no acceleration of burning, does not at all contradict the aerodynamic nature of the acceleration of pre-detonational burning, as long as we do not forget that the formation of the impact wave is a result of the acceleration of burning in parts of the tube near the point of ignition and distantly removed from the point of the origin of the detonation, i.e., in those parts of the tube in which exist the movement of the gas and the turbulence, necessary for the acceleration of the flame.

c) The effect of the shifting of burning on the formation of the detonation. From the aerodynamic point of view, it is easy to explain the otherwise incomprehensible effect of the small shift of ignition from the butt-end of the tube on the origin of the detonation. It turns out that if the mixture is ignited not in the proximity of the butt-end of the tube, but several centimeters from it, then the detonation originates considerably closer to the beginning of the tube than in cases of ignition directly at the butt-end of the tube. It is easy to see that in this case, the initial speed of the movement of unburned gas gradually increases, which facilitates the acceleration of burning, from the viewpoint elaborated earlier here.

It must be noted in conclusion that the theory of the transformation of slow burning into detonation in tubes deserves attention in connection with the problems of techniques of explosion safety and in connection with the necessity for a clear conception of the possible causes of the acceleration of burning to high speeds and the causes of the origin of impact waves in the burning of gas- and dust-air mixtures.

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