theory of relativity. But, it is necessary to keep in mind that for elementary particles the concrete character of the connection between the mass and the properties of space does not necessarily have to correspond to the particular requirements of the theory, which are confirmed only for macrophenomena.

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202

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Phenomena in the Vicinity of Detonation Formation in a Gas

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Phenomena in the vicinity of a detonation are discussed. It is shown in particular that in accordance with a previously developed theory[1,2] explaining how slow burning combustion turns into a detonation, a detonation can occur in gas both at some distance in front of the slow combustion as well as in its immediate vicinity.

INTRODUCTION

THE mechanism whereby slow combustion of a gas in a tube turns into a detonation was discussed earlier[1,2] and can be summarized briefly as follows: The expansion of the slowly-burning mixture causes motion and turbulence of the unburned gases. The turbulence increases the velocity of propagation of the combustion relative to the gas, and this in turn causes an increase in the velocity of the gas--the combustion accelerates progressively.

The accelerating combustion, acting like a piston moving in a gas-filled tube, produces an adiabatic-compression wave. The slope of the adiabatic-compression wave front increases progressively until a state and velocity discontinuity occurs in the gas. At the instant that the discontinuity occurs, its surface separates the undisturbed and uncompressed adiabatically compressed gas, the velocity of which is readily computed from the velocity of sound in the gas on both sides of the discontinuity.

From the theory of random discontinuities[3] it is known that such a discontinuity of state and velocity cannot propagate in the gas; it breaks into a shock wave, which travels through the unperturbed gas, and a rarefaction wave, which propagates in the opposite direction, through the adiabatically-compressed gas. At the place of shock-wave formation the gas experiences a density and temperature discontinuity, the surface of which is stationary relative to the gas. The gas temperature in the shock wave rises sharply because of the non-adiabatic shock compression. This leads to a detonative ignition of the uncombusted gas--to the formation of a detonation.

Once certain assumptions are made, the entire process lends itself readily to analysis; this was done with an accuracy to within constant multipliers in the reference quoted[2]. The fact that in most cases the explosion actually occurs not in a single plane but over a certain length of the tube does not affect the argument substantially. It produces no change whatever in the qualitative picture of the detonation phenomenon and reduces only insignificantly the accuracy of the computation of the distance between the ignition point and the location where the detonation occurs.

In principle it is possible also to suggest another mechanism for the pre-detonation acceleration of the combustion in the tube, proposed by L. D. Landau, and based on the instability of the plane combustion front and the self-turbulence of the gas in the region of the flame. In tubes, however, it is the turbulence produced by the walls that always precedes the self-turbulence and determines the acceleration of the flame. To observe the self-turbulence it becomes necessary to employ special measures to prevent formation of turbulence due to the walls[4].

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[1] K. I. Shchelkin, Dokl. Akad. Nauk SSSR 23, 636 (1939)

[2] K. I. Shchelkin, J. Exper. Theoret. Phys. USSR 24, 589 (1953)

[3] Ia. B. Zel'dovich and K. I. Shchelkin, J. Exper. Theoret. Phys. USSR 10, 569 (1940)

[4] Kh. A. Rakipova, Ia. K. Troshin and K. I. Shchelkin, Zh. Tekhn. Fiz. 17, 1397 (1947)

The above brief description of the elementary theory of the transition from slow combustion into detonation does not lead to any essential or fundamental objections. There exist, however, contradictions between theory and experiment, and these call for a special analysis and for more rigor in the elementary theory developed earlier. This contradiction is due to the following: From the scheme described above it follows that the detonation should always occur at a certain distance forward of the accelerating-flame front. This follows directly from the mechanism by which the discontinuity forms forward of the front of the accelerating combustion. In fact, however, the detonation occurs almost always directly at the accelerating-flame front. Regardless of the theory, a detonation that forms forward of the accelerating combustion front is observed only in rare cases; for example, in mixtures of carbon monoxide and oxygen.

This article is devoted principally to an analysis of the above contradiction. Clarifying this contradiction requires analysis of the phenomena occurring near the site of the detonation, which is equivalent to analysis of several cases where a slow combustion changes into a detonation.

1. OCCURRENCE OF DETONATION AT A CERTAIN DISTANCE FORWARD OF A SLOW-COMBUSTION FRONT

The analysis is best carried out by using a numerical example. Let the acceleration of a slow combustion in a diatomic gas, which is initially at atmospheric pressure, result in an adiabatic-compression wave of finite pressure, say 10 atmospheres (Fig. 1 *a*), and let an increase in the slope of the wave turn its front into a discontinuity at section *A* of the tube.

If we represent the adiabatic wave as a sum of low-intensity compression waves rapidly following each other (Fig. 1 *b*), then the discontinuity will occur in Section *A* of the tube at the instant when all the low-intensity waves catch up with each other and combine at section *A* (Fig. 1 *c*). At the instant the discontinuity is formed, the gas is adiabatically compressed to ten atmospheres on the left of the explosion plane and is at the initial atmospheric pressure on the right of the explosion plane. The values of the densities, temperatures and velocities of the gas in both sides of the explosion are given in Fig. 1 *c*.

Figure 2 shows the picture of the phenomenon some time Δt after the discontinuity has formed. The discontinuity plane A_0 has moved during the time Δt at a distance $\Delta t \times 2.05\ c_0$ to position *A*, where c_0 is the velocity of sound in the uncompressed gas. The discontinuity is broken up into a shock wave, the front *C* of which, with a pressure of 9.1 atmospheres, has moved through the tube a distance $\Delta t \times 2.82\ c_0$, and into a rarefaction wave, the front of which is located at the time Δt in plane *B*. At the same instant that the adiabatic

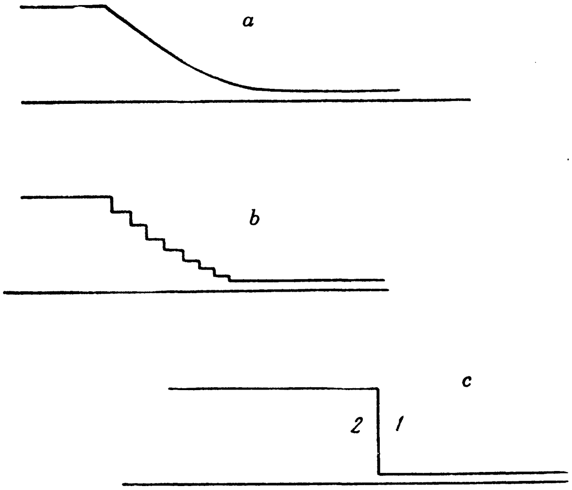

FIG. 1. Formation of state and velocity discontinuity in gas.
a--adiabatic compression wave at $p = 10$ atmospheres;
b--the same wave, represented as a sum of weak compression waves;
c--adiabatic discontinuity of state: *1*--$p_1 = 1$ atm, $w_0 = 0$, ρ_0, T_0, c_0: 2-- $p = 10$ atm, $w = 1.95\ c_0$, $\rho = 5.16\rho_0$, $T = 1.93\ T_0$.

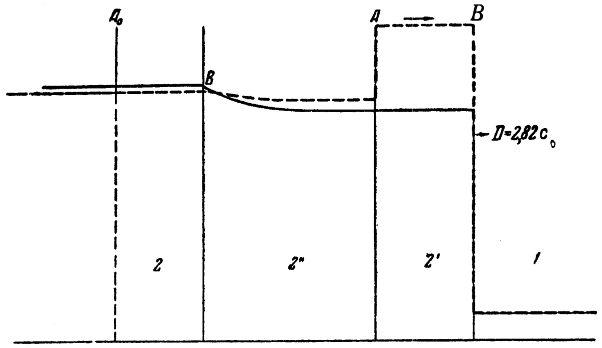

FIG. 2. Separation of discontinuity into a shock wave and rarefaction wave. Solid line = pressure; dashed line = temperature. *1*--unperturbed gas at p_0, T_0, c_0 and ρ_0; *2'*--state of gas in shock wave moving at a velocity D: $p = 9.1\ p_0$, $w = 2.05\ c_0$, $\rho = 3.8\ \rho_0$, $T = 2.46\ T_0$; *2''*--state of gas in rarefaction wave: $p = 9.1\ p_0$, $w = 2.05\ c_0$, $\rho = 4.84\ \rho_0$, $T = 1.88\ T_0$: 2--adiabatic discontinuity of state: $p = 10\ p_0$, $w = 1.95\ c_0$, $\rho = 5.16\ \rho_0$, $T = 1.93\ T_0$.

discontinuity breaks up and the shock wave is formed, a gas density and temperature discontinuity is formed in plane A_0; this discontinuity is at rest relative to the gas and moves with the gas and at the same velocity as the gas behind the front of the shock wave. At the instant Δt the plane of this discontinuity is located in position A. The values of the velocity, temperature and density in various locations in the tube are given in Fig. 2.

As already indicated the gas can ignite and detonate at the site of the shock wave formation. The ignition can occur either practically instantaneously, or after the lapse of a certain ignition delay time τ_0. In Fig. 3, point A represents the site of the discontinuity formation, line A_0B the motion of the shock-wave front, and line A_0A the motion of the temperature and density discontinuity. Line A_0C of the same figure represents the motion of the front of the flame.

Point D in the figure shows the detonation ignition of the gas, occurring at a time t after the formation of the discontinuity at point A_0 and at a distance l forward of the slow-combustion front. At point D, in addition to the detonation wave DO which moves forward, there also occurs a compression wave, partly caused by the detonation wave DR, which moved backwards, opposite to the slow flame. It is evident that only by coincidence will the delay time τ be such that the detonation occurs at the instant the front of the flame arrives at the discontinuity plane A.

It is interesting to note that after forming at point D (Figs. 3 and 4), the detonation moves through the compressed and moving gas to the intersection with line A_0B. In this section the speed of the detonation relative to the tube walls is often experimentally observed to be considerably greater than after the detonation moves into the gas at rest beyond the line AC.

2. FORMATION OF DETONATION NEAR THE SLOW-COMBUSTION FRONT

From the preceding Section it follows that the detonation can occur at a distance forward of the flame before the slow combustion arrives at the discontinuity plane (at line A_0B, Fig. 3). However, it may happen that no detonation ignition occurs in the shock wave. What will occur if the temperature in the shock wave is not high enough to cause detonation ignition of the gas?

In this case the flame, in the final analysis, will catch up with the plane of the temperature and density discontinuity A (Fig. 2), and after passing through the temperature discontinuity plane, will move from a colder medium to one heated to a considerably higher temperature. In Fig. 4 the intersection between the flame and the discontinuity plane is shown by the intersection between the line $B'D$ of the front of the flame and line A_0A. In the example given above, the flame passes from a medium with an approximate temperature of 290° C into a medium with an approximate temperature of 450° C.

It is natural to expect the speed of propagation of the flame at such a transition at point D to increase sharply (with a jump) so that a second shock wave DM forms in the adiabatically-compressed and heated gas, propagates through the

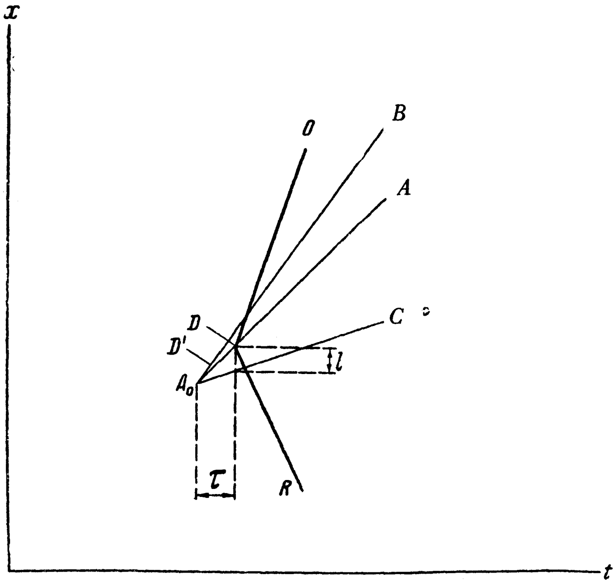

FIG. 3. Appearance of detonation forward of the flame front.

gas compressed by shock wave A_0B (Fig. 4), and heats the gas further. This additional acceleration of the combustion and the resulting additional increase in temperature of the uncombusted gas can lead to a detonation ignition of the gas at point D or in its vicinity on line DM, and to the formation of a detonation wave DO (Fig. 4). If even this temperature rise in the second wave DM is insufficient for detonation ignition of the gas, the detonation will not occur at all under the given conditions.

The description above explains quite clearly the origin of the second shock wave, which plays a substantial role in the formation of the detonation in the case when the detonation does not originate in the first wave A_0B, Thus, a second wave is possible only in the presence of the fundamental shock wave (A_0B in Fig. 4). In other words, its formation is possible only if the speed of propagation of the undetonated flame suddenly increases at point D, i.e., if the velocity of the pre-detonation combustion turbulence increases with the temperature of the gas. According to the elementary theory of turbulent combustion, the speed of a flame in a strongly turbulent stream is independent of the normal speed of the flame with an accuracy to within a slowly-varying function and is consequently independent of the temperature. However, the strong (quadratic) dependence of the normal speed on the temperature ($\sim T^2$) causes a considerable acceleration of the flame both here and also when the speed of the turbulent combustion does not depend strongly on the normal speed. Therefore, in the case under consideration the slowly variable function in the relationship between the turbulent and normal speeds of the flame cannot be neglected, nor can the possibility of such an acceleration be denied thereby. For quantitative evaluation of the intensity of the second shock wave, occurring at point D of Fig. 4, it would be very important to know the form of this slowly-varying function.

3. PHENOMENON OF ''DRAWING'' THE FLAME TO THE SITE OF THE DETONATION

It is important to note that before the appearance of the detonation at point D of Fig. 4, the flame experiences an acceleration relative to the tube walls at section B'-D. This acceleration is due to the flame falling into the rarefaction wave, the front of which moves against the flame, while the gas velocity is directed along the motion of the flame. Because of this, the flame is accelerated in the rarefaction wave. In the actual example (Fig. 2) the speed of gas in the rarefaction wave from the plane B to the plane A increases by several dozens of meters per second (by approximately $0.1\ c_0$).

It is possible that in this case, gas turbulence causes the flame not merely to travel faster, but also to overtake the gas itself. In view of the short time involved, the turbulence may not propagate from the walls over the entire section of the tube, and the flame may move more rapidly along the walls of the tube, in the zone where the turbulence is higher.

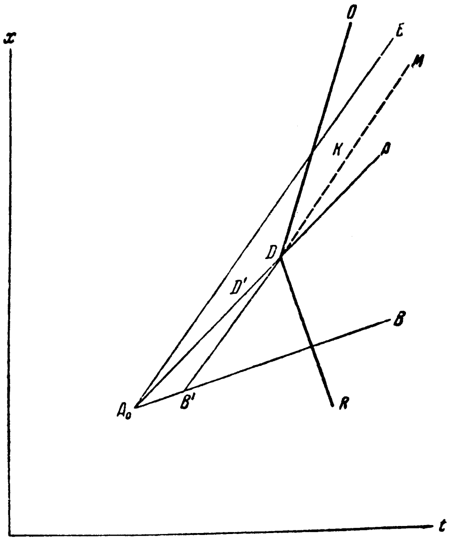

FIG. 4. Formation of second shock wave and appearance of detonation in the immediate vicinity of the flame front.

In view of the above, the acceleration of the flame in the rarefaction wave may contribute somewhat to the formation of the detonation. In certain cases the detonation may occur even before the front of the flame arrives at the temperature discontinuity (to line A_0B of Fig. 4) for example, in point B', at a certain small distance forward of the front of the flame.

4. FORMATION OF DETONATION IN THE PRESENCE OF UNEVENNESS OR ROUGHNESS

The entire detonation picture changes substantially in a tube that is uneven or rough inside. Roughness in the initial portion of the tube contributes strongly to the acceleration of the slow combustion, and to the formation of the shock wave A_0B. This problem was discussed earlier[1,2].

In addition to affecting the acceleration of the slow flame, roughness (as was already indicated earlier) can contribute to the transformation of a slow combustion into a detonation, because the gas temperature rises sharply wherever the shock wave front strikes a projection (a roughness). The temperature rise in a shock wave reflected from an obstacle depends on the intensity of the wave and can easily be computed.

In the case shown in Fig. 3, the detonation may be caused by local overheating of the gas when the shock wave is reflected from a rough or uneven spot, for example, at point D'. The delay period of the detonation combustion in this case cannot be long, since the gas will not stay very long at the location where the shock wave is reflected by the rough spot, but it will be swept away by the stream and will be diluted by gas that is less heated. The delay period is therefore not shown in Fig. 3.

In the case shown in Fig. 4, the second shock wave *DK* occurs at the point *D* as a result of the transformation of the flame into heated gas. If this wave is incapable of initiating the detonation at point *D*, the motion of its front, as mentioned above, can be represented by line *DM* of Fig. 4. The reflection of the second wave from the rough spot or obstacle, say at point *K*, can also cause detonation provided, naturally, that it has not occurred earlier.

In conclusion, it must be noted that when the shock wave is formed not in a single plane (point A_0 of Figs. 3 and 4), but over a certain length of the tube, as is more likely, the qualitative picture of all these phenomena in the vicinity of the detonation does not change substantially.

It must also be pointed out that the arguments given in this work supplement rather than change those conclusions made earlier[1,2] and mentioned briefly in the beginning of this article concerning the mechanism by which slow combustion transforms into detonation.

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176