

DETONATION WAVES IN GASES

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Usp. Fiz. Nauk 80, 525-551 (August, 1963)

1. Introduction.	523
2. Structure of detonation wave.	524
2.1. Stationary zone of chemical reaction.	524
2.2. Rarefaction wave.	525
2.3. The Chapman-Jouguet condition.	526
2.4. Diverging and converging detonation waves.	526
3. Experimental methods for the study of the state of the gas behind the detonation front	527
3.1. Measurement of pressure (pulsed piezoelectric transducers)	527
3.2. Measurement of gas density.	528
3.3. Measurement of gas temperature (generalized method of spectral line inversion).	528
3.4. Determination of the chemical composition and concentrations of individual mixture components.	529
4. Features of ignition of gas behind a shock wave.	529
4.1. The induction period.	529
4.2. Determination of kinetic reaction parameters.	531
4.3. Formation of detonation front.	531
5. Transition from combustion to detonation in gases.	532
5.1. Gas dynamic scheme of formation of detonation in a tube.	532
5.2. Calculation of the state of the mixture ahead of the flame front.	532
5.3. Compression wave and adiabatic self-ignition.	533
5.4. Interaction of flame with shock wave.	533
6. Oscillations of gas behind the detonation front.	534
6.1. Causes of oscillating combustion mode.	534
6.2. Properties of transverse waves.	535
6.3. Acoustic theory of spin detonation.	536
6.4. Structure of spin detonation front.	536
6.5. State of gas in a detonation wave with account of transverse pulsations.	537
7. Detonation in stationary gas stream.	537
7.1. Combustion of gas behind a stationary shock wave.	537
7.2. Stationary spin detonation.	538
7.3. Pulsating combustion behind a shock wave in a supersonic stream.	538
8. Conclusion.	538
9. Literature.	539

1. INTRODUCTION

DETONATION waves form a complex aggregate of interrelated physical and chemical processes. The detonation problem has therefore, in addition to being of technical importance, attracted the attention of many researchers from different branches of knowledge. The establishment of thermodynamic equilibrium behind the detonation front, gas oscillations and spin detonation, the transition from slow combustion to detonation, detonation limits, and combustion and detonation in supersonic gas streams—all are problems closely related to the singularities of shock waves, the rates and mechanisms of chemical reactions, turbulence, acoustic oscillations, and other processes in gases. The study of detonation was not limited to the development

of the classical Chapman-Jouguet analysis. Considerable deviations from this analysis, connected with singularities of the compatibility of the physico-chemical and hydrodynamic processes in gas media, have been noted long ago.

To investigate detonation phenomena it was necessary to develop very precise microsecond pulse methods for measurements of different quantities: pressure, density, temperature, emissivity and absorptivity of a gas in different spectral regions, chemical composition, and concentration. Progress in the techniques of shock-wave measurements in tubes^[1-4] has made it possible to employ many of the developed methods to study ignition dynamics and to determine the state of the gas behind the detonation front.

We consider in this article the most interesting re-

sults on fast processes in detonation waves. The foreign reviews^[5-7] cover the modern status of this problem far from completely, particularly with respect to the analysis of the work of Soviet authors. In addition, this subject is not always represented with sufficient breadth in the programs of the international symposia on combustion and detonation. For example, the problem of spin detonation, to which much recent research has been devoted, is certainly not sufficiently discussed. Little attention is likewise paid to the study of the kinetics of the chemical reactions at temperatures corresponding to detonation conditions.

2. STRUCTURE OF DETONATION WAVE

A detonation wave is a modification of discontinuous gas-dynamic flow. A self-maintaining shock discontinuity is produced in a medium capable of exothermic reaction, and a chemical reaction is continuously initiated behind its front as a result of the heating by adiabatic compression. The detonation speed is connected with that of the shock wave and amounts to several kilometers per second, which is hundreds of times faster than the velocity of a flame in gases as determined by the laws of heat front propagation. A detailed analysis of the shock adiabat in a detonation and calculations of detonation-wave velocities in different gases are given, for example, in^[7-9]. We consider here only some details of gas flow in a detonation wave.

2.1. Stationary chemical-reaction zone. The physical model of the detonation wave is still unclear in many respects. This pertains most of all to the structure of the chemical reaction zone. The simplest classical one-dimensional scheme was proposed for the process by Chapman and Jouguet. According to this scheme, the chemical reaction occurs in the shock wave instantaneously, and the combustion products expand in the isentropic rarefaction wave that follows the detonation front.

Although in many cases this assumption is sufficient to determine the detonation velocity, many features of detonation waves are connected precisely with the finite rate of the chemical reaction. For example, if the losses due to friction and the heat losses in the reaction zone exceed the influx of energy due to the chemical reaction, then the detonation wave becomes damped; this is known as the "detonation limit." The question of a detonation with losses is analyzed in detail in^[8] on the basis of the assumption that the reaction zone is stationary.

The existence of an extended chemical reaction zone, as will be shown in what follows, leads to considerable deviations from stationary and one-dimensional gas flow behind the detonation front. Nonetheless, the one-dimensional model of a detonation wave with a stationary chemical reaction zone behind the shock front (Ya. B. Zel'dovich^[10,8], and later^[11-13]) make the pattern of the phenomenon much more pre-

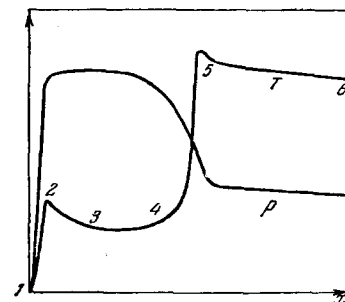


FIG. 1. Variation of pressure and temperature behind the detonation front (not to scale).

cise and describe the structure of gas flow in many cases.

The sequence of processes that develop in a detonation wave is illustrated in Fig. 1, which shows schematically the temperature and gas-pressure profiles. The shock transition (1-2), which is completed after several molecule collisions, is followed by rotational and vibrational relaxation—energy exchange between the translational, rotational, and vibrational degrees of freedom of the gas molecules. In the relaxation zone, the gas temperature corresponding to the energy of translational motion decreases, while the pressure and density of the gas increase to equilibrium values.

The relaxation processes occurring in gases at high temperatures have been sufficiently well studied through the use of shock-wave methods^[4,4]. Whereas excitation of molecule rotation is complete after several dozen collisions, the vibrational relaxation continues for 10^4 – 10^6 collisions. At atmospheric pressure and at 1500–3000°K, the vibrational relaxation time of oxygen, for example, is 1.5 to 15 microseconds.

The vibrational relaxation processes, and also possible dissociation of the initial products, precede the chemical reaction, which is completed after 10^{12} – 10^{14} collisions. The reaction zone (3-5) has its own peculiarities. For chemical reactions with sufficiently high activation energy ($E = 20$ – 40 kcal/mole), more than 90% of the total reaction time may be consumed in the latent, induction reaction.^[15]

During the induction period the active centers of the reaction accumulate, and the pressure, density and temperature of the mixture change little. The induction stage of the reaction (3-4) ends with the explosion (4-5). The relation between the induction and explosion times is determined by the reaction mechanism. Figure 2 shows the calculated changes in the pressure behind the front of a one-dimensional stationary detonation in a $2H_2 + O_2$ mixture, for different variations of the reaction rate with the concentration of the resultant product (zeroth, first, and second order reactions)^[16]. The theoretical variation of the pressure and temperature in the intermediate state of the reaction zone with the relative concentration of the reaction products in the same mixture is shown in Fig. 3.

In a steady-state detonation wave, the profile (1-5)

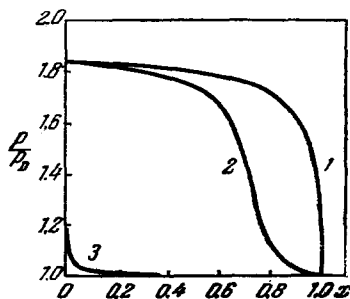


FIG. 2. Pressure profile in the reaction zone. 1 - Zeroth-order reaction; 2 - first-order reaction; 3 - second-order reaction (after [16]).

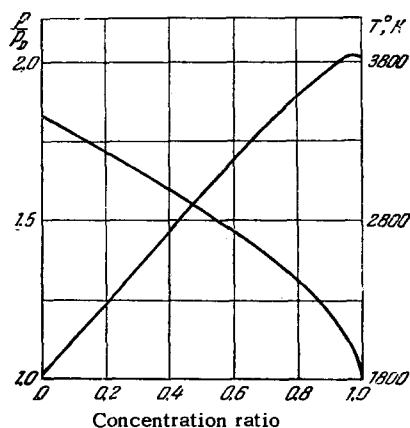


FIG. 3. Pressure and temperature in the reaction zone as functions of the ratio of the running concentrations of the end products to their equilibrium value [16].

is assumed stationary. The structure of the reaction zone is determined by simultaneously solving the hydrodynamic equations of the conservation of mass, momentum, and energy in stationary flow and the equations of chemical kinetics. We must point out immediately that a one-dimensional stationary reaction zone is as a rule not realized in self-maintaining detonation waves. More and more investigations, which will be discussed later on, offer convincing evidence that the gas flow in the reaction zone is far from one-dimensional and is accompanied by intense transverse perturbations. Particularly remarkable are the latest data of D. Hornig [17], who observed deviations from one-dimensionality even in detonation waves in hydrogen-oxygen mixtures at high initial pressures (up to 20 atm). Considerable deviations from one-dimensionality are observed also not only in gases but in the detonation of liquid explosives [18]. The reaction zone borders on a region of nonstationary flow—rarefaction wave (5–6), the profile of which varies in time in accordance with the boundary conditions for the flow of the combustion products.

2.2. Rarefaction wave. The flow of the combusted gas in a one-dimensional rarefaction wave is described by the relations

$$x = (u + a) t$$

and

$$u_2 - u = \frac{2}{\gamma - 1} (a_2 - a),$$

where x denotes the coordinate of the gas particle, u the flow velocity, and a the velocity of sound. The subscript 2 denotes the state of the gas on the boundary between the reaction zone and the rarefaction wave. According to the well-known Chapman-Jouguet condition, the detonation velocity is $D = u_2 + a_2$ (see Sec. 2.3), so that

$$x_2 = Dt = (a_2 + u_2) t.$$

Consequently

$$u_2 - u = \frac{2}{\gamma + 1} \left(\frac{x_2 - x}{t} \right).$$

If we neglect the gas pressure ahead of the detonation front compared with the pressure behind the front, i.e., $p_2 \gg p_1$, then we obtain from the conservation laws

$$u_2 = D - a_2 \approx \frac{a_2}{\gamma}, \quad u_2 - u = \frac{2a_2}{\gamma} \left(\frac{x_2 - x}{x_2} \right).$$

Thus, in the case of detonation in a long tube, the velocity of the combusted gas decreases linearly with the distance from the front over a distance x . When $x = x_2/2$ we have $u = 0$, that is, starting with this point, the gas in a tube with a closed end will be at rest relative to the walls of the tube. If the detonation wave is initiated at the open end of the tube, the gas velocity reverses its sign at the point $x = x_2/2$. The distribution of the gas pressure is determined in analogous fashion:

$$\frac{p}{p_2} = \left(1 - \frac{\gamma - 1}{\gamma} \frac{x_2 - x}{x_2} \right)^{\frac{2\gamma}{\gamma - 1}}.$$

The solid lines in Fig. 4 show the variations of the pressure and velocity along a detonation tube for a detonation initiated at the open end ($x = 0$). The dashed lines correspond to flow with the end of the tube open. The calculation is for $\gamma = 1.2$, which is in close correspondence to the flow of the detonation

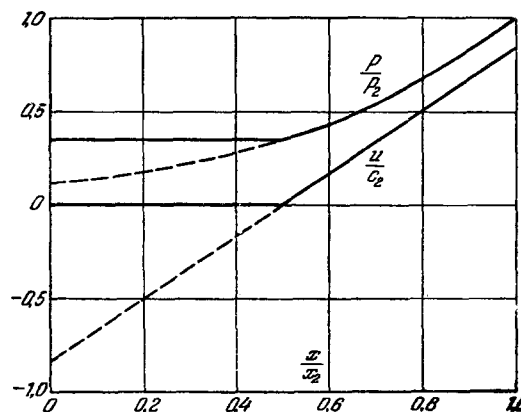


FIG. 4. Structure of flow in a one-dimensional detonation wave. Dashed - open-end tube, x_2 —coordinate of detonation front, $\gamma = c_p/c_v = 1.2$.

products of a mixture of hydrogen with oxygen. An experimental check on the variation of the density in a rarefaction wave for a detonation in a tube is contained in [19].

2.3. The Chapman-Jouguet condition. The borderline between the stationary zone of the reaction and the rarefaction wave is the state of gas defined by the so-called Chapman-Jouguet condition. From the mass and momentum conservation equations for one-dimensional isentropic gas flow we can obtain, by introducing the variable $\xi = x/t$, the following relation:

$$\frac{du}{d\xi} \left[1 - \frac{(\xi - u)^2}{a^2} \right] = 0. \quad (I)$$

Consequently, the position of the boundary of the non-stationary rarefaction wave ($du/d\xi \neq 0$) should be determined from the condition

$$\xi_{fr} = D = u + a,$$

that is, the detonation front should propagate at the velocity of sound relative to the particles of the combusted gas. Thermodynamic considerations lead to the same relation [8, 13].

A few remarks must be made concerning the Chapman-Jouguet condition. This relation serves as the basis for the calculation of the detonation velocity in different gases [9, 20], so that it is important to define precisely the velocity of sound in the combustion products. However, the velocity of sound is not a completely unambiguous quantity, owing to the dispersion caused by slowing down of the excitation of the molecule vibrations. There are all grounds for assuming that the velocity of sound is larger for the high-frequency components than for the low-frequency components. In addition, the calculation of the thermodynamic state of the reaction products from the conditions of chemical equilibrium and the total heat release on the Chapman-Jouguet boundary is not always correct. For example, some reactions involving the dissociation of combustion products can have a lower rate compared with reactions that determine the principal heat release. In this case the Chapman-Jouguet boundary shifts towards the zone of the principal chemical reactions, and the slow reactions will no longer influence the parameters of the stationary zone of chemical transformations. The delay in the dissociation and the existence of non-equilibrium concentrations of the final products on the Chapman-Jouguet boundary are equivalent to a higher heat release in the wave compared with the equilibrium calculation. As a result, the detonation velocity may turn out to be higher than the equilibrium value, and the gas pressure in the Chapman-Jouguet state may also increase. An increase in the pressure will contribute to a suppression of dissociation and to a shift of the Chapman-Jouguet boundary towards higher heat release within the limits of the stationary reaction zone (Fig. 5). Thus, a correct choice of the detonation velocity should take into account the shift of the boundary

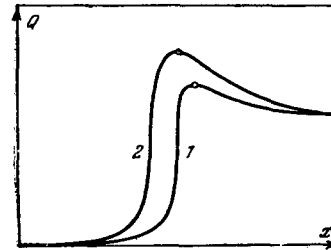


FIG. 5. Shift of heat-release curve in the reaction zone, due to the delay of the dissociation and to the increase in the detonation velocity. 1 - Change in heat release behind the front of the normal detonation wave with increasing distance from the shock front; 2 - the same curve with account of the increase in the detonation velocity and the pressure. The Chapman-Jouguet state is close to the maximum point.

of the stationary zone of the reaction in accordance with the increase in the total heat release and the pressure in this zone. This interesting feature of the detonation-wave structure was first pointed out by Ya. B. Zel'dovich [9, 10]. There are also experimental data which point to the possibility of the existence of such combustion modes in a detonation wave [21]. However, as was already noted, such an effect can be complicated to some degree by deviations from the one-dimensionality of the gas flow in the vicinity of the detonation front.

2.4. Diverging and converging detonation waves. By considering three-dimensional detonation waves with spherical or cylindrical symmetry, we can obtain a clear idea of the wide range of applicability of the Chapman-Jouguet analysis (plane and diverging waves), as well as of the existence of physically motivated deviations from this scheme ("focusing" or converging waves). For three-dimensional non-plane waves Eq. (I) has a right-hand part, which is in itself evidence of the possibility that the wave distribution may not be stationary. An analysis of gas flow in diverging detonation waves [8, 22, 23] has shown that in diverging flow behind the front only the law governing the expansion of the gas in the rarefaction wave adjacent to the reaction zone changes. The motion of the wave remains stationary, as is confirmed by experiments in which undamped spherically [24] and cylindrically [25] diverging detonation waves were observed. We must point out as a curious fact that, according to (I), large gradients of the velocity and of the other parameters of the gas behind the detonation front should exist for a stationary diverging wave in the Chapman-Jouguet state. This circumstance has raised at one time doubts concerning the possible existence of diverging waves without damping (Jouguet).

Whereas a change in the law of expansion of the combustion products behind the detonation front has no effect on the wave velocity, this holds true only up to certain limits when it comes to the additional compression. By artificially increasing the compression

behind the detonation front, say with the aid of a piston inserted in the tube behind the wave, it is possible to compensate partially or fully for the pressure drop in the rarefaction wave that follows the reaction zone^[26]. In this case the stationary nature and the detonation velocity remain unchanged. However, if the piston velocity is made larger than the velocity of the gas particle stream in the Chapman-Jouguet state, then the velocity of the detonation front increases, in accordance with the conservation laws on the shock discontinuity, and will depend on the piston velocity. This gives rise to a so-called "overcompressed" detonation^[27].

As shown by Ya. B. Zel'dovich, in a converging detonation wave the overcompression occurs spontaneously as a result of the decrease in compression in the focusing stream. Using the tendency of the detonation to remain stationary, we can calculate the change in pressure in the wave front during the course of its focusing^[28]. In the limit, for very small converging-front radii, the behavior of the detonation wave will differ little from the focusing of a shock wave, that is, the released chemical energy can be neglected compared with the work of compression in the converging stream. The asymptotic law of increase in pressure in the wave front can be determined from the known solutions^[29].

3. EXPERIMENTAL METHODS FOR THE STUDY OF THE STATE OF THE GAS BEHIND THE DETONATION FRONT

The chemical reaction behind the detonation front is completed within a very short time interval. For example, in the detonation of a mixture of hydrogen with oxygen, the period of induction of the reaction behind the shock front is approximately 2 microseconds at atmospheric pressure. Consequently, the resolution in the measurements of the time variation of the different physical quantities in a detonation wave should be at least less than 10^{-6} sec. Let us consider briefly some methods for such measurements (a more detailed description is found in^[3]).

3.1. Measurement of pressure (piezoelectric pulse transducers). The most accurate and convenient method of measuring pressure behind a shock wave front is to use pulse transducers made of piezoelectric ceramics^[4,30-32]. Transducers of tourmaline, quartz, Rochelle salt, and other natural piezoelectric materials are less sensitive, unreliable in operation, and are more prone to parasitic oscillation inside the piezoelectric element.

The pressure-measuring accuracy and the resolution time of the transducers can be improved in essentially two different ways. One is to reduce to a minimum the linear dimensions of the element and the other is to attempt to create in an element of finite dimensions conditions that are suitable for the propagation

of an elastic wave and permit exact determination of the pressure acting on the sensing surface.

The construction of a piezoelectric pulse transducer for the measurement of gas pressure on a tube wall is shown in Fig. 6. The cylindrical element of barium titanate ceramic is soldered to a long zinc rod which absorbs without reflection the elastic wave propagating in the element whenever the gas pressure changes abruptly. The acoustic impedances of zinc and barium titanate are nearly equal in magnitude^[30]. To eliminate the acoustic coupling between the element and the walls of the tube, the space between the case and the rod is filled with beeswax or some other "decoupling" filler. Samples of pressure records in a detonation of the mixtures $2\text{H}_2 + \text{O}_2$, $2\text{CO} + \text{O}_2$, and ethyl alcohol with oxygen in a shock tube are shown in Fig. 7. The diameter of the element in such a construction can be reduced to 1–1.5 mm with the sensitivity maintained at ~ 10 V-pF/atm. The resolution of the transducer can reach 0.5 microsecond.

In^[31] is described the operation of a piezoelectric pulse transducer which results in high time resolution with a large element. In this case the pressure $p(t)$ acting on the sensing surface is determined from the recorded rise time of the charge $q(t)$ in the element

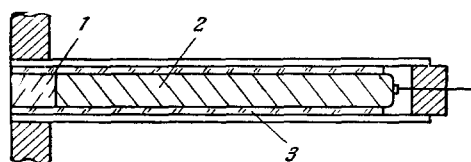


FIG. 6. Pulsed piezoelectric transducer for pressure. 1—Piezoelectric-element; 2—zinc slug; 3—wax layer.

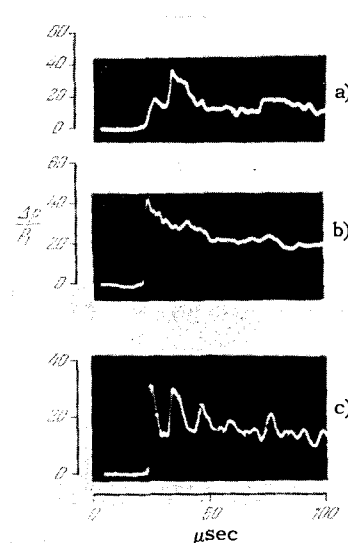


FIG. 7. Oscillograms of pressure behind a maintained detonation in a shock wave of square cross section. a) Mixture of carbon monoxide with oxygen, b) mixture of ethyl alcohol vapor with oxygen, c) mixture of hydrogen with oxygen. Initial gas pressure 0.1 atm.

as the elastic compression wave propagates in it:

$$q(t) = A \int_0^t p(t) dt.$$

The pressure under normal reflection of a detonation wave from a rigid wall was measured by this method accurate to 0.5 microsecond, and the existence of an increased-pressure region corresponding to the chemical-reaction zone was demonstrated thereby.

3.2. Measurement of gas density. The Schlieren method^[3,4,33] and the interferometer method^[34-36] are extensively used to measure the gas density behind the shock wave front. Both methods are based on the registration of the change in the refractive index of the gas, and are very sensitive (changes up to 0.1% ρ_1 are registered). Figure 8 shows an interference pattern of the structure of the stream behind the detonation front in the mixture $2\text{H}_2 + \text{O}_2 + 0.92 \text{Xe}$ ($p_1 = 40 \text{ mm Hg}$). The vertical displacement of the interference fringes is proportional to the change in the gas density.

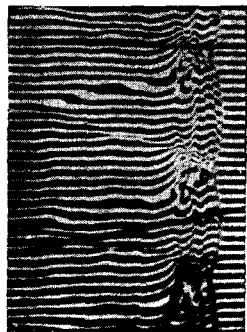


FIG. 8. Interference pattern of the propagation of a detonation in the mixture $2\text{H}_2 + \text{O}_2 + 0.92 \text{Xe}$.

The minute details of the flow registered with the interference instrument may make it difficult to obtain data on the average density near the detonation front. Consequently the most convenient method of measuring density in detonations is by absorption of a thin beam of x-rays perpendicular to the motion of the front of the wave^[19,21,37-39]. To increase the absorbing ability of the gas it is necessary to add in this case an inert gas, usually xenon, to the investigated mixture. The change in radiation intensity is registered with a photomultiplier equipped with a scintillator. Figure 9 shows a comparison of the calculated and measured profiles of the detonation-wave density in a $2\text{H}_2 + \text{O}_2 + 0.92 \text{Xe}$ mixture with an initial mixture pressure of 44 mm Hg. The observed discrepancy cannot be attributed merely to the limited resolution of the density-measuring method. The detonation waves registered in Figs. 8 and 9 have been obtained under practically identical conditions^[36,38]. As can be seen from Fig. 8, the detonation shock front is not a plane surface and is strongly disturbed by transverse waves (see Sec. 6.2 below). Therefore density measurements by x-ray absorption define not a one-dimensional chemical-

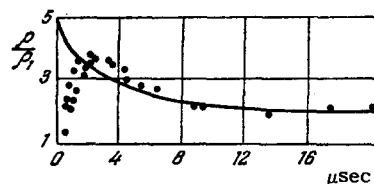


FIG. 9. Results of experiments on the measurement of the density behind a detonation front (x-ray absorption).

reaction zone, but some profile of density variation which is averaged over the front.

In the experiments of D. Hornig^[17] the change in the gas density behind the detonation front was registered by reflecting light from the surface of the front. This method has made it possible at one time to determine with high resolution (on the order of the wavelength of light) the structure of the shock wave in ordinary gases^[40]. Measurements in detonation waves have shown that the jump of the gas density on the front corresponds to a shock transition without a chemical reaction. However, the effective width of the reaction zone has turned out to be much larger than expected. For example, in a $2\text{H}_2 + \text{O}_2$ mixture with initial pressure of 20 atm, the width of the transition region amounts to approximately 2.5 mm, which is hundreds of times larger than the width of the one-dimensional reaction zone obtained from kinetic data. These results offer evidence of considerable deviations from one-dimensionality even at high mixture pressures.

3.3. Measurement of gas temperature (generalized method of spectral line inversion). This method has turned out to be the most convenient in the study of the state of a gas behind a shock-wave front^[41-44]. Whereas to determine the gas temperature in the detonation of condensed substances it is sufficient to measure with a pyrometer the emissivity in two sections of the continuous emission spectrum^[45-47], in the detonation of a gas it is necessary to determine independently both the emissivity and the absorption of the light in the spectral regions of the intense emission of the gas or of the impurities contained in it. If the emission spectral lines of the impurities are used to measure the gas temperature (see^[41,42] and also the reviews^[1,48]) the resolution is limited by the time necessary to heat, evaporate, dissociate, and excite the impurities (for example, sodium salts) within the volume of the gas behind the shock wave. By the same token, the possibility of measurements near the shock front is excluded. Thus, for the sodium D-line emission behind the front of a shock wave in air, the delay in thermal equilibrium can amount to several times ten microseconds^[42].

In^[49] an attempt was made to measure the temperature behind the detonation front in an acetylene-oxygen mixture, using the inversion of the emission lines of the gas proper. Such measurements were made possible by the high concentration of the inter-

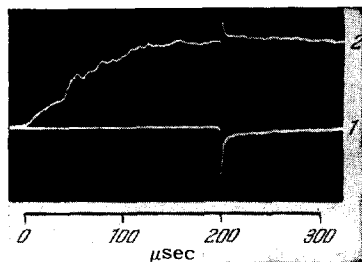


FIG. 10. Oscillograms of the emission of gas behind a detonation front in the mixture $C_2H_2 + O_2$, $\lambda = 5165 \text{ \AA}$.

mediate radical C_2 in the chemical-reaction zone. Figure 10 shows oscillograms of the emission of the gas (1) and of the gas with additional illumination from a standard light source (2). The comparison source used in these experiments was a krypton-xenon flash lamp, the color temperature of which can reach $5000^\circ K$. The resolving power of such measurements amounts to 0.5×10^{-7} sec. The gas temperature measured at different concentrations of the acetylene-oxygen mixture components is close to the theoretical equilibrium value.

3.4. Determination of the chemical composition and concentrations of individual mixture components. Spectral methods are used extensively here, too. For example, a method for determining the concentration of molecular oxygen by measuring its absorption in the ultraviolet region has been thoroughly developed^[1,50]. If the dependence of the absorptivity of molecular oxygen on the temperature and concentration is determined by experiment, then the change in absorption behind the shock front will determine uniquely the change in the absolute concentration of the oxygen in the mixture. As indicated in^[51], an oxygen layer 1 cm thick at room temperature and at a pressure of 1 mm Hg absorbs approximately 30% of the transmitted light in the $\lambda = 1470 \text{ \AA}$ region. The method of absorption spectroscopy in the ultraviolet is successfully used for the determination of the dissociation rate of pure oxygen and of oxygen in air in strong shock waves^[50].

In analogy with research carried out in flames^[15,52], the kinetics of the chemical reactions behind the front of shock and detonation waves can be investigated by observing the time variation of the absorptivity of some intermediate reaction products. For example, in^[53] a study was made of the reaction of decomposition of water vapor behind a shock wave front. The measurements were carried out at $2400\text{--}3200^\circ K$ in the hydroxyl absorption region $\lambda = 3064 \text{ \AA}$.

Non-equilibrium concentrations of the carbon monoxide and atomic oxygen were observed in the reaction zone behind the front of a detonation in a $2H_2 + O_2 + 2CO$ mixture. The emissivity of the gas in individual spectral portions of the visible region was found to be proportional to the product of the concentrations $(CO) \times (O)$ ^[36]. The amplitude of the emission in the reaction zone corresponded in these experiments to the reac-

tion-product concentration calculated without account of the slow recombination reactions occurring in triple collisions. The reaction-zone length registered in this manner amounted to several millimeters at an initial gas pressure $p_1 = 0.1\text{--}0.3$ atm. Measurements have shown that data on the reaction-zone parameters are closest to the results of the one-dimensional calculations only in the "overcompressed" waves, while self-maintaining detonation waves exhibit strong deviations from one-dimensionality.

Thus, while having sufficiently well developed methods for physical measurements of detonation waves, we have so far no reliable data on the state of the gas directly behind the detonation front. The difficulties arising here are not methodological but of principal character, since the existing limitations are connected primarily with the appreciable deviations of the gas flow behind the detonation front from one-dimensionality. The causes of these deviations will be considered in the sections that follow.

4. FEATURES OF IGNITION OF GAS BEHIND A SHOCK WAVE

The thermodynamic state of a gas behind a detonation shock wave is determined by the rate of its propagation and the initial pressure of the mixture. The gas temperature is usually $1500\text{--}2000^\circ K$, which at pressures on the order of atmospheric corresponds to an ignition delay of approximately 1 microsecond. The kinetics of the chemical reactions under such conditions have been little investigated, so that the applicability of any known reaction mechanism to the high-temperature interval must be specially checked by experiment. To study the kinetics of the emission at microwave delays, effective use is made of shock waves^[54-62]. The shock wave method has many advantages over other chemical-kinetics methods, for in fact it excludes the thermal influence of the vessel walls. In addition, the temperature interval of the shock-wave investigations is much broader than that of ordinary methods.

4.1. The induction period. To study the dependence of the mixture induction period on the temperature and on the pressure, we can use the method of reflected waves. The mixture ignition conditions are governed in this case by the state of the gas behind the wave front in the tube following its reflection from the closed end. Figure 11 shows a time sweep of the ignition process in an $H_2 + O_2$ mixture, obtained by the Schlieren method.

The initial mixture was compressed twice—behind the incident wave 1 and behind the reflected wave 2. The state of the gas behind the front of these waves is homogeneous, and the gas particles behind the wave front 2 are at rest relative to the tube walls. The pressure, density, and temperature of the gas are usually determined by gas-dynamic calculations. A check on

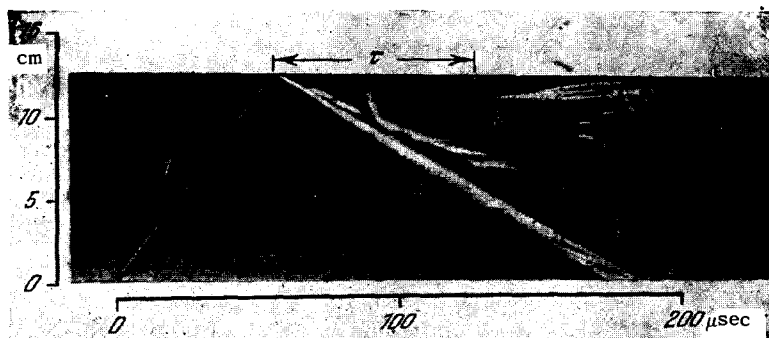


FIG. 11. Schlieren photograph of delayed ignition in an $H_2 + O_2$ mixture.

the validity of such a calculation, made by independently measuring the pressure with piezoelectric transducers and the density with an interferometer and by the Schlieren method, has led to a deviation not exceeding 1–2%. Thus, for example, Fig. 12 shows the gas flow velocity behind wave 1 in a $2CO + O_2$ mixture, obtained by measuring the slope of the contact lines on the Schlieren photographs^[3]. The experimental points usually lie somewhat above the calculated curve, and this serves as a measure of the deviation from the one-dimensionality in the shock tubes^[3,63].

A chemical reaction develops inside the volume of gas heated by the shock wave. In order not to exclude the effect of gas heating in the incident wave 1, the ignition induction period is usually measured with respect to gas layers that are adjacent to the reflecting wall. Since the gas ignition occurs immediately at several points of the gas volume 3, the values of τ (see Fig. 11) are extrapolated to τ_w ^[55]. Centered ignition of the gas, which begins in the form of combustion from individual centers, ends with explosion and formation of the detonation wave 4.

Figure 13 shows the results of measurements of the delays in the ignition in an $H_2 + O_2$ mixture at atmospheric pressure in the temperature interval from 1000 to 1600°K. The reaction kinetics of this mixture at lower pressures and temperatures is sufficiently well known, so that the data obtained can be compared with the delays determined by the chain mechanism of this reaction^[15,64,65]. During the induction period, at not

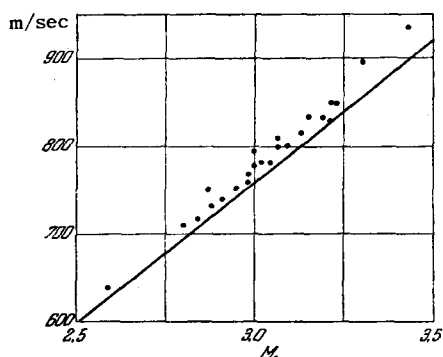
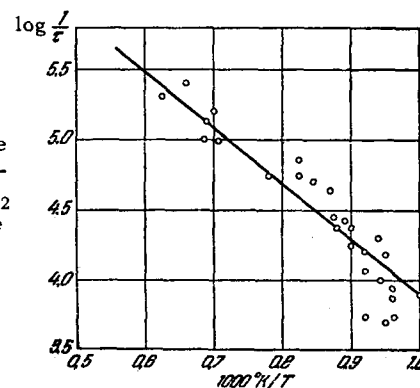


FIG. 12. Comparison of calculation and experiment for the flow velocity behind a shock wave in a $2CO + O_2$ mixture; $p_1 = 0.15$ atm.

FIG. 13. Temperature dependence of the induction period of an $H_2 + O_2$ mixture. Continuous line — calculation.



too high concentration of the reaction products, its velocity is determined by the branching velocity

$$\frac{d(H_2O)}{dt} = \frac{d(H)}{dt} = 2k_2(O_2)$$

The velocity constant of this reaction is determined in^[64,65]. The activation energy ranges from 18 to 16 kcal/mole. The calculated temperature dependence of the induction period is shown by the line of Fig. 13 ($E = 18$ kcal/mole). As can be seen from the plot, at high temperatures there is good agreement between experiment and calculation, in accordance with the chain theory. Analogous results have been obtained also in dilute mixtures, where the measurements are less reliable, owing to the presence of the diluents^[57,61].

At low temperatures the delays increase more rapidly than can be expected from calculation. A similar conclusion was obtained in^[66] from a comparison of the measurements made by several workers. We present the summary data on the ignition of a hydrogen-oxygen mixture taken from^[66], and supplement them with our own results^[55] (in^[66] there is reference only to the experiments of^[59] in incident shock waves). As seen from Fig. 14, the kinetic curve has a characteristic bend near $T \sim 1100^\circ K$. The change of the reaction rate is connected in this case with the approximation to the limit owing to the formation of the HO_2 radical and the suppression of the branching. In this case the character of the explosion in the gas also changes qualitatively: whereas the detonation away from the limit is initiated as a rule at the first center, a relatively slow development of a series of ignition

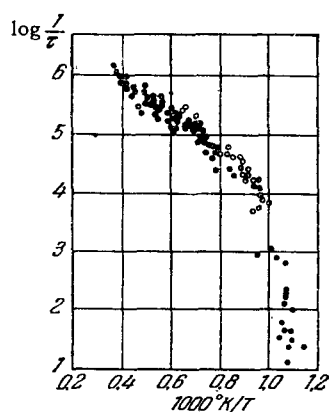


FIG. 14. Temperature dependence of the induction period of hydrogen-oxygen and hydrogen-air mixtures. ●—summary data^[66], ○—from^[55].

centers is always observed near the limit. In the region where the velocity of the leading reaction changes, it is incorrect to estimate the effective activation energy from the slope of the kinetic curve so that the value 90 kcal/mole obtained in^[66] for the low temperature region should be considered too high.

It must be noted that during the induction period (see Fig. 11) the change in density of the reacting mixture is less than 1%. This shows clearly that the accumulation of active reaction centers occurs with negligible heat release (the thermal effect of the gross reaction goes into formation of high non-equilibrium hydrogen atom concentrations).

Thus, the data obtained confirm the correctness of the chain theory up to the pressures and temperatures that prevail in detonations. It is therefore natural to expect the limiting kinetic phenomena also to be connected with some hydrodynamic features of the detonation waves (see Sec. 6.4).

4.2. Determination of kinetic reaction parameters.

By using experimental data on the temperature dependence of the induction period we can obtain the effective activation energy of the leading reaction from the slope of the $\log 1/\tau$ vs. $1/T$ line. For many reactions, the experimental curve is nearly a straight line, and the obtained activation energy agrees with the values de-

termined by other methods (for example, reactions of hydrogen with chlorine, bromine, and iodine^[67]). In some cases, however, for example in the ignition of mixtures of hydrogen, carbon monoxide, and some hydrocarbons with oxygen, the dependence is more complicated, as we have seen with hydrogen as an example. Consequently the determination of the activation energy for such reactions is difficult.

If the reaction mechanism is known, the experimental values of the induction period can be used also to determine the pre-exponential factor in the Arrhenius law for the temperature dependence of the rate of the regulating reaction. From the data given above on the ignition of a mixture of hydrogen and oxygen, for example, we get $k_2 = 1.8 \times 10^{-10}$ cm³/sec, which agrees with^[64] and^[65]. The table lists experimental values of the activation energy for some mixtures, and indicates the range of the thermodynamic parameters of the gas state, for which the ignition was investigated.

4.3. Formation of the detonation front. As can be seen from Fig. 11, a detonation wave is formed following the occurrence of an ignition center inside an adiabatically heated gas mixture. Depending on the gas temperature and pressure, the time of formation of the detonation front varies from several microseconds to a value on the order of 100 microseconds. It must be noted that in undiluted actively reacting mixtures the detonation wave is produced within the compressed mixture independently of the shock wave front that causes the heating of the gas. In dilute mixtures, a gradual acceleration of the reflected shock wave to detonation velocity is observed after the region of gas ignition coalesces with its front^[58,61].

When mixtures are ignited under low temperature conditions, the detonation is formed in two stages: the expanding combustion products are first compressed adiabatically and heat a certain volume of the non-combusted mixture adjacent to the flame front, followed by explosion of the compressed gas and formation of a detonation front, analogous to the ignition in shock tubes. This type of ignition in shock tubes is

Composition of mixture	H ₂ +O ₂	2CO+O ₂	CH ₄ +2O ₂	C ₂ H ₅ OH+3O ₂	C ₇ H ₁₆ +11O ₂ +97%Ar	C ₃ H ₈ +air
Temperature of gas in experiments on ignition, °K	1000—1540	1200—1400	1050—1200	1100—1300	1500—2400	880—1030
Gas pressure, atmosphere	1±0.2	4±0.5	7±0.2	3.8±0.3	3—20	14
Effective activation energy for the induction period, kcal/mole	17.3±1.5	Varies	27.4±2.5	11.5±2.0	30	19
Bibliography	55	3, 56	3	56	58	54

called in the literature transition from slow combustion to detonation.

5. TRANSITION FROM COMBUSTION TO DETONATION IN GASES

The formation of detonation waves as a result of acceleration of a flame in tubes is the subject of an extensive literature. Most papers explain the causes of the acceleration of the visible motion of the flame relative to the tube walls^[68-75], and attempt to construct a most complete gas-dynamic scheme for the process^[7,76-83]. Of greatest interest is the work by K. I. Shchelkin, in which the influence of turbulence on the change in the flame propagation conditions is explained^[68,69]. Without going into details of the history of the question, we describe here the sequence of the individual stages of this complicated nonstationary process. We note that a detailed analysis of the phenomenon has become possible only through application of shadow methods, supplemented by pulsed measurements of the gas pressure^[3,4,26,83].

5.1. Gas-dynamic scheme of formation of detonation in a tube. When the mixture is first ignited, a laminar flame is formed, with a normal propagation velocity on the order of 1-10 meters per second relative to the particles of the uncombusted gas, depending on the mixture. If the mixture is first ignited near the closed end of the tube, the combustion products can expand only towards the uncombusted mixture. This results in a gas flow similar to the expansion of a compressed gas in shock tubes. The expansion of the combusted gas produces in the uncombusted mixture a compression wave in which the gas particles are set into motion with velocities of several hundred meters per second. The flame is also part of this stream, so that its visible velocity increases noticeably.

It must be noted that the arising flow has a complicated character, and the state of the combusted gas is the result first of the transition from the unperturbed gas to the compressed state, followed by combustion in the flame front. Therefore a simplified analysis of the phenomenon, for example by replacing the flame with an impermeable piston moving with the visible velocity of the flame^[76,78], is not sufficiently rigorous.

Depending on the specific flow conditions (transverse tube dimensions, roughness of the walls) and on the density and viscosity of the gas, turbulization appears in the mixture stream, which results in turn in a change of the flame profile and an increase in its surface. The Reynolds numbers for the flow ahead of the flame are usually one order of magnitude larger than the critical values, and the length of the region over which turbulization of the mixture flow is noticeable amounts to several dozen tube diameters for smooth walls.

An increase in the flame surface corresponds to an increase in the compression and to a higher flow velocity, which in turn leads to an increase in turbulization. Heating of the mixture by compression also leads to an increase in the normal velocity of the flame. The process develops until the conditions necessary for adiabatic volume self-ignition of the gas are produced in the compression wave ahead of the flame^[55,83]. The development of turbulence can be accelerated by introducing special obstacles in the form of spirals, grids, etc.^[67,75], and also by the action of the compression waves, reflected from the closed opposite end of the tube, on the flame (see Sec. 5.3).

In Fig. 15 the Schlieren picture of the described process in a $C_2H_2 + O_2$ mixture is aligned with the pressure oscillograms, recorded by a piezoelectric transducer at two points along the tube. The volume character of the explosion of the mixture ahead of the flame is evidenced by the form of the backward compression wave (detonation wave), which consists of several perturbations^[83]. It can be noted that the gas explosion develops in a compression wave that has had no time to change into a shock wave.

5.2. Calculation of the state of the mixture ahead of the flame front. The existing calculation procedures are based on a simultaneous solution of the conservation equations on two discontinuities—on the flame front and on the shock wave that forms ahead of the flame^[7,77]. The simplest procedure for calculating the process is described in^[83]. As can be seen from Fig. 15, the pressure jump in the compression-wave front ahead of the flame is small, and the main increase in pressure occurs in the region of the continuous adiabatic compression. Under such conditions it is advantageous to confine the computations to the simplified system: adiabatic wave-flame-combustion products at rest relative to the tube walls.

The state of the gas in the compression wave is determined by the flame velocity

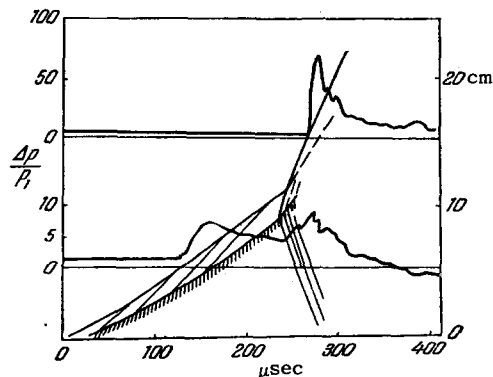


FIG. 15. Schlieren picture and oscillograms of the pressure in the transition from combustion to detonation in a tube. $C_2H_2 + O_2$ mixture^[83].

$$S = S_n \frac{\Sigma}{\sigma},$$

where S_n is the normal combustion velocity, σ the transverse area of the detonation tube, and Σ the effective surface of the flame. For example, for a round tube, replacing the surface of the flame by a hemisphere, we have $\Sigma/\sigma = 2$. If we denote the state of the unperturbed gas by the index zero, the gas ahead of the flame front by 1, and the combusted gas by 2, then the state of the compressed uncombusted mixture at the maximum of the adiabatic compression wave 1 is determined in the assumed scheme from the following conservation laws:

$$\begin{aligned} \rho_1 S &= \rho_2 (S - u) \\ \rho_1 S u &= p_2 - p_1, \\ u &= \frac{2}{\gamma - 1} (c_1 - c_0) \\ \frac{p_2}{\rho_2} &= \frac{RT_2}{\mu_2} \cong \text{const} \end{aligned}$$

Here u is the stream velocity, c the velocity of sound, and T_2 and μ_2 the temperature and molecular weight of the combustion products, which do not change much with variation of p_1 . Confining ourselves to the approximation $T_2 = T_C$ (combustion temperature of the mixture), we can find the dependence of u and T_1 on the effective flame velocity S . Figure 16 shows the results of such approximate calculations for the mixtures $C_2H_2 + O_2$ (I) [83] and $H_2 + O_2$ (II). Thus, conditions for an adiabatic explosion are produced in the first mixture even when $S/S_n = 4.5$, but for the second only when $S/S_n = 20-25$. It is characteristic that the length of the pre-detonation section in the hydrogen-oxygen mixture is larger than in the acetylene-oxygen mixture by precisely the same ratio [4].

5.3. Compression wave and adiabatic self-ignition.

The described mechanism of the formation of detonation in the explosion of an adiabatically heated gas mixture is the most general and is particularly pronounced in stoichiometric active mixtures. In this case the shock front of the wave ahead of the flame does not have time to form during the time of transition, so that the adiabatic calculation scheme is the most valid here.

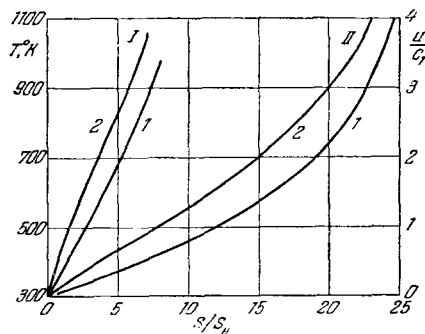


FIG. 16. Approximate calculation of the state of the gas ahead of the flame for the mixtures $C_2H_2 + O_2$ (I) and $H_2 + O_2$ (II). 1) Temperature, 2) Gas flow velocity u/c_1 .

Comparison with experiment for the $C_2H_2 + O_2$ mixture shows that the local inhomogeneities in the vicinity of the flame, and particularly near the walls, cause the explosion of the gas to occur usually at flame velocities 20-30% below critical (temperature difference near 100°) [83].

In mixtures with lower reaction rates and with smaller heat release a shock front of a compression wave can be formed during the pre-detonation stage, but in this case the maximum pressure and temperature will be attained near the surface of the accelerated flame. In this case the procedure for calculating the gas state needs to be refined to account for the appearance of the shock transition. This does not mean that the principal role in the detonation should be assigned to the formation of the shock wave ahead of the front. As already noted, the detonation wave occurs as the result of explosion of the compressed mixture, and not after the coalescence of the flame with the shock wave, as is sometimes assumed [7, 71, 77]. It is interesting to note that in some cases the accelerating combustion region can overtake the compression wave front and travel together with it for some time in the form of a single complex, without a detonation [75]. A Schlieren photograph of such a process in a $C_2H_2 + O_2$ mixture is shown in Fig. 17.

5.4. Interaction of flame with shock wave. Investigations along this line are connected with the peculiarities of the transition from combustion to detonation in limited volumes. The compression wave produced by the flame in a tube of finite length experiences several refractions through the combustion region, causing additional deformations of the flame surface and increasing the normal combustion velocity due to the increase in the temperature (both effects increase the velocity S). The increase in the flame velocity is connected with the appearance of an additional compression of the gas, which is manifest in the experiments by an intensification of the refracted waves [84-86]. For a relative estimate of the effect of different factors on the increase in the flame velocity, investigations of the interaction between shock waves and the flame are best carried out in shock tubes [87, 88], when the state behind the front of the shock wave is established independently and is well known. Figure 18 shows a Schlieren photograph of a collision between a shock wave and a flame in a $C_2H_2 + O_2$ mixture. The flow past the first collision of the wave with the flame is in good agreement with the one-dimensional gas-dynamic calculation of the decay of an arbitrary explosion, in which the flame after the collision is regarded as a contact surface. The main intensification of the shock wave is observed after it is reflected from the end of the tube and refracted again through the combustion region (explosion of gas and formation of detonation behind the reflected wave). The intensification of the reflected wave depends essentially on the deformation of the contour of the flame, which increases the combustion surface.

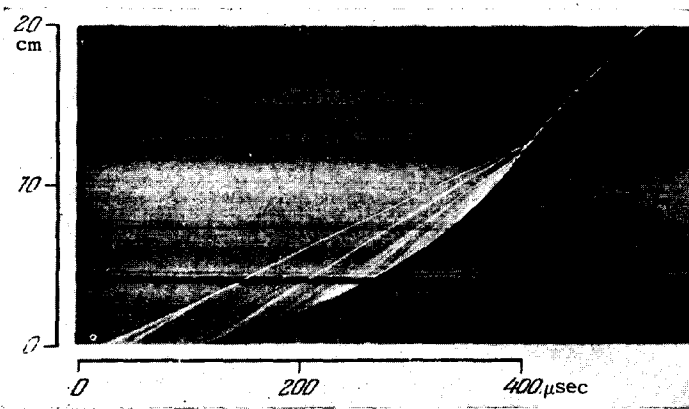


FIG. 17. Schlieren photograph of flame motion in the case of formation of a compression wave—flame complex. Mixture $C_2H_2 + O_2$; $p_1 = 30$ mm Hg.

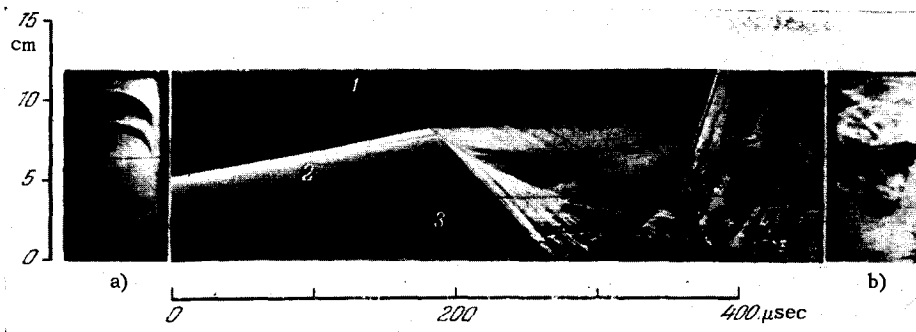


FIG. 18. Schlieren photograph of the refraction of a shock wave on the flame front (sweep). 1—Shock wave front; 2—flame prior to collision, 3—refracted wave. Still photographs of the shape of the flame front before and after the collision are shown alongside.

For low-amplitude shock waves the increase in the normal velocity of the flame plays a lesser role. This is clearly manifest in the sharp decrease of the intensification of the shock wave following its double refraction through the flame when the place of collision is shifted to the reflecting wall, where the possibility of non-one-dimensional deformations of the flame surface is practically excluded^[88]. The peculiarities in the intensification of the compression waves in the turbulent combustion zone are considered in^[89].

It is typical that only the change in the normal combustion velocity with temperature is taken into account in calculations of the intensification of acoustic and shock waves interacting with a flame^[85,86,90], while the effect of flame deformation is not considered. At the same time, the role of flame front instability in processes where the combustion goes over into detonation^[68,69] is sufficiently well known. Thus, in the propagation of a spherical flame^[24] or of flames in tubes of large cross section, the increase in the flame surface due to the appearance of its internal Landau instability^[91] is apparently the main cause of the increased flame velocity.

6. OSCILLATIONS OF GAS BEHIND THE DETONATION FRONT

The one-dimensionality of the flow behind a plane detonation front is usually violated by the occurrence of oscillations in the gas. Numerous observations^[92-103] offer evidence that the oscillating or "spin"

detonation mode is the most widespread form of detonation combustion. It has also been ascertained that the amplitude and frequency of the oscillations are not only determined by the pressure and the chemical composition of the mixture, but depend also on the gas flow conditions behind the detonation front. For example, in the case of detonation in shock tubes, additional compression of the combusted gas leads to an intensification of the oscillation^[26] and to the appearance of secondary pressure waves^[95]. In addition, it is well known that the oscillation frequencies can coincide in many cases with the natural frequency of the oscillations of the volume of the combusted gas. We must emphasize immediately that the source of the oscillations in the gas are layers adjacent to the detonation front, that is, the reaction zone, so that the causes of the oscillations must not be sought in the singularities of the flow of the combusted gas. In the case of "radiation" of oscillations by the detonation front, the parameters of the radiated waves may sometimes be matched to the frequencies of oscillations in the combusted gas. In such cases the acoustical phenomena are most clearly pronounced, owing to the appearance of self-oscillating systems. We shall discuss this in detail in Sec. 6.3.

6.1. Causes of the oscillating combustion mode. The flow of gas behind the detonation front is hydrodynamically unstable^[104-107]. This instability is connected with the existence of a finite chemical reaction zone and with the induction period of the ignition. As shown by K. I. Shchelkin^[104], the boundaries for the appear-

ance of oscillations behind the shock front can be estimated in the following manner.

The combustion in the detonation wave may become nonstationary if the change in the induction period of the mixture, brought about by the change in the temperature in the arising perturbations, is of the same order as the induction period itself. The range of variation of the pressure behind the detonation front can be estimated by the difference $p_{sh} - p_d$ between the pressure of the uncombusted gas and the Chapman-Jouguet pressure. Therefore a criterion for the loss of stability can be expressed in the form

$$\frac{d\tau}{dT}(T_1 - T_{sh}) \geq \tau \quad \text{or} \quad \frac{E}{RT_{sh}} \left[1 - \left(\frac{p_d}{p_{sh}} \right)^{\frac{\gamma-1}{\gamma}} \right] \geq 1,$$

where E — effective activation energy for the leading reaction of the induction period. This condition is sufficiently well satisfied for $E > 15-20$ kcal/mole, that is, for the majority of mixtures used in laboratory practice. The stability of the detonation front against small perturbations was investigated in [106]. The structure of the reaction zone in this investigation differed little from the simplified scheme of K. I. Shchelkin [104]. V. V. Pukhnachev [105] considered the question of the stability of a Chapman-Jouguet wave with a one-dimensional finite reaction zone. In these investigations, instability was obtained for all the detonation cases of practical interest.

6.2. Properties of transverse waves. The chemical reaction zone in the detonation wave is deformed and breaks up into a series of perturbations which move over the surface of the shock front. For mixtures with large reaction rates, the produced oscillations have the largest amplitude and a high frequency, while in slowly reacting mixtures and near the concentration or pressure limits, the amplitude of the oscillations increases appreciably and their frequency decreases.

The characteristic dimension determining the frequency of the oscillations is connected with the size of the chemical-reaction zone. The linear dimensions of the vessel in which the detonation wave propagates influence the frequency and character of the produced oscillations only if the average distance between two successive perturbations becomes comparable with the smallest dimension of the vessel, for example with the tube diameter [98]. Such a condition is satisfied, for example, by spin detonation, which will be considered separately.

The oscillation frequency and the average dimension of the "cells" into which the detonation front breaks up depend essentially on the properties of the mixture. This is most convincingly evidenced by the results of experiments with diverging detonation front [25], in which there are no reflecting boundaries in two or three dimensions. In the experiment illustrated in Fig. 19, the detonation wave is produced in a tube and then goes out to the center of a flat round shallow

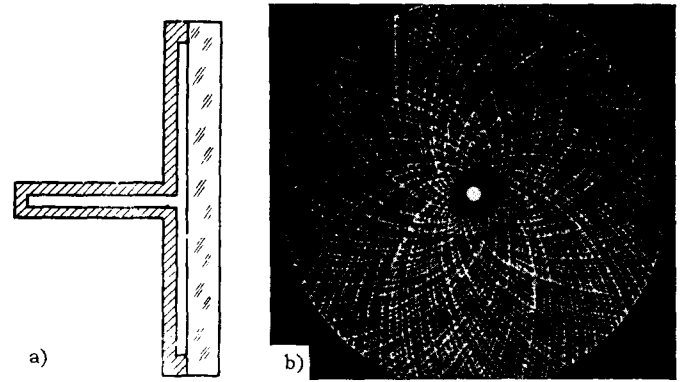


FIG. 19. Experimental setup (a) and sweep photograph (b) in a diverging detonation wave.

channel. The plane of the channel is focused on a stationary photographic film. A series of light spots moves over the detonation front in a transverse direction, and the tracks of the spots trace on the film trajectories in the form of logarithmic spirals

$$r \frac{d\varphi}{dt} = c.$$

The glowing spots are the points of intersection of the transverse waves with the detonation front.

The tangential velocity of the perturbations is in the mean constant and exceeds somewhat the velocity of sound in the combusted gas. The average number of transverse waves per unit length of front periphery, with the exception of the vicinity of the center of the channel, remains constant and depends only on the composition and the initial pressure of the mixture. Track prints obtained by reflection of spherically divergent detonation waves from a wall coated with lampblack also offer evidence of the "cellular" structure of the detonation-front surface.

Let us consider now the condition for the existence of an undamped detonation with intermittent ignition behind the front. The combustion of the gas behind the shock front of such a wave is essentially localized in the region where the transverse compression wave joins the shock front. The transverse wave forms with the ignition region a stable self-oscillating system, in which the thermal energy released in the gas is used partially to maintain the transverse wave in accordance with the known Rayleigh principle, which stipulates that in order for acoustic oscillations to be excited in the gas the heat must be released in phase with the compression.

If the average velocity of the ignition region is higher than the velocity of sound in the combusted gas, it "breaks away" from the acoustic wave and loses the support on the flank. If, to the contrary, the ignition has a smaller transverse velocity, the compression wave, leading the region of ignition, loses its source of energy and becomes attenuated. Thus, a self-maintaining mode is possible only if the average velocity of

the transverse waves, with account of their mutual collisions, is equal to the velocity of sound in the combusted gas^[3,108].

The connection between the acoustic phenomena and the singularities of the ignition behind the detonation-wave front is most clearly manifest in the case of spin detonation in round tubes. Unlike the waves in flat channels, a self-oscillating system is produced, connected with the phase wave of the acoustic oscillations. It is interesting to note that the transverse velocity of the phase wave with a compression antinode near the wall is almost double the velocity of sound in the combusted gas.

6.3. Acoustic theory of spin detonation. The transverse velocity of the ignition section is determined experimentally in the case of spin detonation in round tubes from the angle between the generatrix and the spiral track left by the wave on the side surface of a lamp-black coated tube. For most mixtures in which stable rotation of a single transverse wave is observed ("single-head" detonation), the angle is close to 45°, that is, the transverse velocity is close to the detonation velocity^[92]. This fact is explained by the acoustic theory of spin detonation, proposed by N. Manson^[109,107,110]. It must be noted that the acoustic treatment of spin detonation in the form developed in^[107,109] indicates only a quantitative connection between the transverse velocities of the ignition zone with the parameters of the acoustic waves in the combusted gas. This cannot serve as a basis for stating that the natural oscillations in the volume of the combusted gas cause the "spin" combustion in the detonation wave. We have here only one manifestation of internal instability of combustion behind a shock front, under conditions that are most favorable for this purpose. Therefore the physical analysis of the causes of oscillations and transverse waves in detonation must deal primarily with the singularities in the flow in the chemical-reaction zone behind the shock front, and not with the processes in the combusted gas.

Figure 20 shows a Schlieren photograph of the flow for spin detonation in a round tube. Behind the detona-

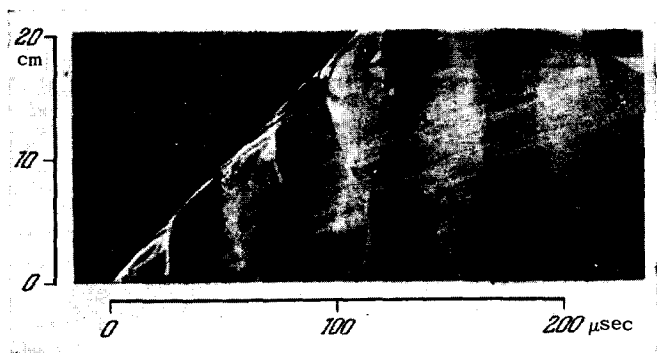


FIG. 20. Schlieren photograph of spin detonation in a 2CO + O₂ mixture in a round tube.

tion front there is a transverse wave which is stretched out along the generatrix of the tube and which appears periodically in the photograph in the form of bright vertical strips. This wave, sometimes called a loop, rotates together with the igniting section of the front. The existence of such a wave agrees with the solution of the wave equation for the radial and tangential oscillations of the volume of gas combusted in the tube. This solution describes rotation of the phase pressure antinode of a complex oscillation with the transverse velocity, determined from the relation

$$v_{per} = \lambda_k R c,$$

where λ_k are the eigenvalues of the Bessel functions, R is the radius of the tube, and c is the velocity of sound.

For the first harmonic, for example in the 2CO + O₂ mixture, $v_{per} = 1.84c = 1780$ m/sec. The detonation velocity of this mixture is $D = 1787$ m/sec, that is, practically the same as the velocity of the transverse wave. We see therefore that in the case of spin detonation the ignition is stabilized by the compression phase wave occurring in the combusted gas.

If a cylindrical insert is placed inside the detonation tube, the transverse velocity of the phase wave should decrease. Suitable experiments^[111] have shown that the observed decrease in the transverse velocity of the loop agrees completely with the calculation for the acoustic wave in a coaxial tube.

6.4. Structure of spin detonation front. Careful investigations of the form of the shock front in a spin detonation wave in a 2CO + O₂ mixture have led to the scheme shown in Fig. 21^[32,97,112,113]. The lines shown in the figure are the intersections of the corresponding shock discontinuity surfaces with the surface of the round-tube channel, the internal surface of the tube being developed on a plane. The arrows indicate the direction of the incoming gas stream. The region of intense gas glow is shaded. The front structure was studied by Schlieren photography supplemented by measurement of the pressure on the tube wall. During the photography, the longitudinal and transverse displacements of the ignition section were compensated for by suitably moving the photographic film at the same resultant velocity^[112].

The mixture burns in two portions of the shock

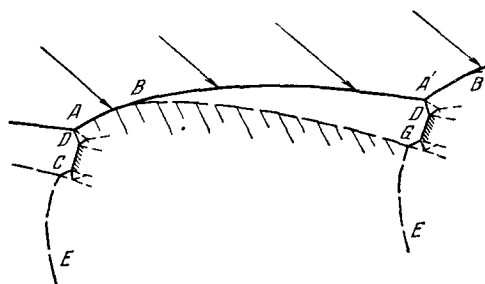


FIG. 21. Structure of shock front in spin detonation.

front: in the most curved section of the main shock front AB and in the transverse wave DE. Such a distribution of the combustion is connected with the kinetic singularities of the ignition of this mixture. Gas-dynamic calculation has shown that separation of the ignition front from the main shock front (point B) corresponds to a temperature $T_{ig} = 1530^\circ\text{K}$ behind the shock wave. Account must be taken of the fact that the sections of the front with larger curvature have a higher velocity, while in the remaining part of the shock front, BG, which makes a sufficiently acute angle with the stream lines of the incoming fresh gas, the temperature decreases. As shown by measurements in shock waves^[3], in the interval $1200^\circ < T < 1500^\circ\text{K}$ the kinetic curve for the $2\text{CO} + \text{O}_2$ mixture goes over from a region corresponding to ignition delays on the order of a microsecond to delays on the order of a millisecond. Thus, the splitting of the ignition front is attributed to the chemical properties of the given mixture.

The uncombusted heated mixture, which is compressed in the section BG of the shock front, is ignited in the transverse wave DE, which closes off the flow. The flanks of the transverse wave form triple shock configurations, which match the flow of the gas in this wave with the shock front and with the loop^[113].

Measurement of the pressure with pulsed piezo-electric transducers with elements having dimensions on the order of 1 mm fully confirmed the presented flow scheme^[32]. The maximum pressure measured behind the front of the transverse wave was $160 p_1$, patently evidencing the combustion of a twice-compressed mixture. The measured pressures are much higher than the maximum pressures ($\sim 50 p_1$) obtained by calculation in which a break or an oblique shock is introduced in the spin-detonation front^[8,103,114]. The introduction of a triple shock configuration can likewise not yield a value larger than $50 p_1$ ^[114]. Experimental data^[32,113] have shown clearly that the Shchelkin-Zel'dovich model^[8] is not realized experimentally, and that behind the shock front of a spin detonation wave there are anomalously high gas pressures, connected with the double shock compression of the gas before the ignition in the transverse waves.

6.5. State of the gas in a detonation wave with account of transverse pulsations. Under conditions where the flow is essentially not one-dimensional it is necessary to take into account the pulsation components of the velocity, density, and gas pressure in the conservation laws on the shock discontinuity. The final state described by the Hugoniot equilibrium adiabat is modified in this case and differs from the one-dimensional state, since part of the released heat energy is transformed into pulsational-motion energy, which is essentially equivalent to an increase in the effective specific heat of the gas. In addition, the pulsation motion produces an additional pressure in the medium, and the detonation velocity increases as a whole. An analysis

of the shock adiabat of the detonation under the assumption that pulsational motion arises behind its front in the form of isotropic turbulence, was made by D. White^[36]. A qualitative picture of the influence of the turbulence pulsations on the flow in the wave is shown in Fig. 22. The shock transition transforms the gas from the initial state O to the final state B' (without reaction), and the straight line OB' crosses the equilibrium adiabat of one-dimensional detonation CAD at two points, C and D. The intermediate states of the gas in the chemical-reaction zone will now lie not on a straight line (such as BA in the one-dimensional wave), but on some curve such as B'A'D, which passes through the point A' where the local Chapman-Jouguet condition is satisfied (the dashed curves show the shock adiabat with account of loss of part of the thermal effect to excitation of the turbulence).

Following state A', the pulsation motion attenuates and the flow becomes one-dimensional, that is, the final state approaches the equilibrium adiabat CAD. Two cases are apparently possible: if the detonation as a whole is self-maintaining, the stationary reaction zone terminates with the gas state D on the lower branch of the equilibrium adiabat, and in the case of large extraneous "overcompression" of the detonation a transition to the point C of the upper branch becomes possible.

The assumption of isotropic turbulence in the combustion zone results in a lucid picture of the influence of the pulsational motion on the flow of the gas, but does not fully correspond to reality. In fact, behind the detonation front we have not disorderly turbulent mixing, but a system of acoustic waves with fully defined parameters. Therefore the foregoing analysis is essentially of qualitative interest and can be useful in the construction of a more complete scheme of the detonation wave.

7. DETONATION IN STATIONARY GAS STREAM

Many new data on the conditions for the compatibility of the combustion of the gas with the igniting shock wave were obtained by studying the detonation produced in compression shocks in continuous gas-mixture streams. Let us consider the principal lines followed by these investigations.

7.1. Combustion of gas behind a stationary shock wave. This form of combustion was studied in wind

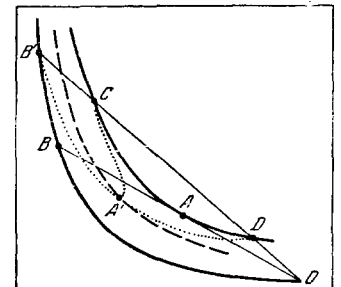


FIG. 22. Shock adiabat of detonation with account of transverse pulsations behind the front.

tunnels^[115-117]. The difficulties in obtaining stationary detonation in a supersonic gas stream are connected with the high Mach numbers for detonation waves. For stoichiometric mixtures usually $M_D \sim 5-7$ whereas in the case of adiabatic deceleration of flow stream behind a shock wave with $M_1 = 3.5-4$ (see Sec. 4) the gas temperature is already sufficient for rapid self ignition. Thus, the production of detonation streams for stoichiometric mixtures has low probability, owing to the high deceleration temperature and the ignition on the walls or during mixing.

If the velocity of the incoming mixture stream is lower than the detonation velocity, the detonation wave produced upon deceleration by an obstacle breaks away from the stabilizing body and moves off upstream. Figure 23 shows successive frames of such a process, obtained under conditions of supersonic flow decelerated by a projection in a shock tube^[59].

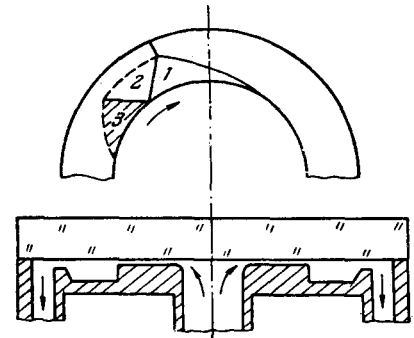
Stationary shock tubes with ignition of gas behind the front were obtained only in dilute hydrogen-air mixtures^[115,116]. When hydrogen is added to the supersonic stream of hot air, a change was observed in the form of the compression shock produced on the obstacle, and an extended combustion zone was observed behind the shock front.

7.2. Stationary spin detonation. In analogy with spin detonation, V. V. Voitsekhovskii^[118] has produced a scheme for continuous ignition of gas moving with detonation velocity (Fig. 24). A fresh mixture is fed continuously into an annular channel in the radial direction through a narrow subcritical gap. The combusted mixture is also removed in the radial direction. An igniting shock wave is produced in the channel, and its propagation is maintained by combustion behind its front of a fresh mixture fed to the channel during the time of one revolution of the shock wave. The velocity of the shock wave in such an experiment turns out to be smaller than the detonation velocity, since the inflow of fresh mixture and the combustion of the gas occur only in a small section of the shock front (the



FIG. 23. Formation of detonation behind a compression shock in a shock tube. Velocity of incoming stream is lower than the detonation velocity. Picture speed is 40,000 frames per second.

FIG. 24. Gas combustion behind a shock wave circulating in an annular channel. 1) Fresh mixture, 2) compressed gas before ignition, 3) combustion products.



combustion region is shown shaded in the figure). In this case the stationary hydrodynamic process with gas combustion behind a shock wave differs from the Chapman-Jouguet detonation scheme. Such a process is perfectly stable. Its duration was determined in the experiments by the reserve mixture supply and could last several dozen seconds.

7.3. Pulsating combustion behind a shock wave in a supersonic stream. Periodic ignition of the gas behind the front of a shock wave, produced at the surface of a body in a supersonic stream, was observed in ignition of gas mixtures by a flying bullet^[119]. A periodic structure of the stream behind the igniting shock wave was observed in analogous investigations^[120]. The oscillations of the gas stopped only when the velocity of the flying body was appreciably increased.

A study of this phenomenon, carried out in a shock tube^[121], has shown that the periodicity of the ignition is connected with the detachment of the gas combustion region from the front of the shock wave as the gas expands sharply following the ignition. Such a detachment of the combustion was observed also in experiments^[122] where the detonation propagated in a tube whose cross section was abruptly increased. Separation of the fronts was observed also in^[123,124].

Notice should be taken of the effective use of shock tubes in experiments on ignition in stationary supersonic streams. The tube is used in this case as a wind tunnel with a short operating time. The advantages of such a device lie in the fact that the attainment of high enthalpy in the produced supersonic stream of the mixture does not entail preliminary heating of the gas to high temperature prior to its escape, making it possible to carry out the investigation in mixtures that are prepared beforehand, without mixing in the stream.

8. CONCLUSION

In concluding this review of the latest progress in the study of detonation in gases, we must point out several problems which call for further development and search for new solutions. This pertains first of all to a clarification of the general conditions of compatibility of the chemical and hydrodynamic processes. The universality of the non-one-dimensional mechanism of combustion behind the detonation flame is still a puzzle.

The problem of stability of flow in a detonation with a finite chemical reaction rate has not yet been fully solved. The mechanism of the connection between the acoustic phenomena in the combusted gas and the process of ignition behind the shock front is still unclear. Strictly speaking, there should be no such connection in classical detonation, since the perturbations must not penetrate behind the Chapman-Jouguet plane. It is possible that an important role is played here by the losses in the detonation wave.

There is no doubt that the structure of the detonation waves with high reaction rates should be influenced by the thermal and diffusion processes, since large temperature, density, and concentration drops exist in the front of the detonation. So far we have only theoretical estimates^[125] and qualitative explanations of some observations^[16] in this direction.

In the question of the transition of combustion into detonation, the general laws governing the mechanism by which the flame velocity increases on going over to the turbulent gas-flow mode still remain unexplained. If general schemes to interpret this process are found, the gas-dynamic analysis of the phenomenon and the description of the final explosion phase of the process should raise no serious difficulties.

Notice must also be taken of the practical importance of developing various schemes for detonation combustion in continuous gas streams. Stationary combustion behind a maintained shock wave can apparently be used in engines or, for example, in various methods for chemical processing of gases, where high-temperature heating followed by abrupt cooling of the mixture during the reaction process are necessary.

Finally, in the study of chemical gas reactions at high temperatures, the use of detonation waves can supplement research in shock waves, by which many fundamental results in high-temperature kinetics have been obtained^[1,3,67]. An important place should be assigned in such research to spectroscopic measurements.

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