DEVELOPMENT OF COMBUSTION IN AN ISOLATED PORE

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It is known [1, 2] that under certain conditions the combustion of gas-permeable porous systems is disturbed as a result of the penetration of combustion into the pores (interior) of the material. The nature of the convective combustion predetermines the consequences of this penetration and, hence, the explosion effect.

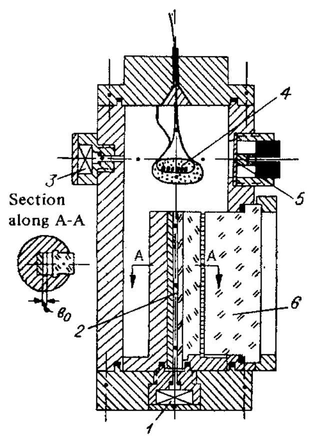

Fig. 1. Diagram of the manometric bomb used to investigate the development of combustion in an isolated pore.

An investigation of the occurrence and development of convective combustion [3, 4] is difficult because in general the convective combustion front is not plane. Therefore, in the case of nontransparent (solid) explosives, optical methods that record the luminescence at the lateral surface of the charge do not give a sufficiently complete and objective picture of the development of the process. Moreover, a porous explosive is a disordered system of pores of complex geometry. Accordingly, it is convenient to employ a simplified ordered model. As such a model we selected an isolated pore formed by two thin (2–3 mm) plane-parallel plates of solid (nonporous) material. The pore was enclosed in a strong casing of plexiglas and metal. Ignition took place at one end; the opposite end was either sealed (closed pore) or left open (open pore). The geometry of the pore was determined by the length (depth) L and the distance b_0 between the plates, which characterizes the equivalent hydraulic diameter of the pore d_e. For the plane pore employed $d_e \simeq 2b_0$.

The development of combustion in the pore was investigated in a manometric bomb (Fig. 1) with a large free volume, so that it was simultaneously possible to obtain an optical record of the process and register the pressure directly in the pore with the bottom end closed. In the bomb there was a transparent plexiglas window 6, and two piezoelectric transducers, one of which (transducer 3) recorded the pressure $p_c(t)$ in the bomb chamber, while the other (transducer 1) recorded the pressure directly in the pore $p_p(t)$; device 5 was provided for quenching the specimens by dumping the pressure.

The propagation of combustion along the pore was registered with a high-speed motion-picture camera or photorecorder. The signals from the piezoelectric transducers were passed through an amplifier and recorded on a double-beam oscillograph. The pore was ignited with a convective flow of hot gas formed by burning igniter 4, which created the initial pressure in the bomb within a period of 5–10 msec. Thus, the igniter essentially created the conditions of migration of the gaseous products along the pore characteristic of a "walled-in charge" [5].

Some of the experiments were conducted in a constant-pressure bomb, the initial pressure in the pore being equal to the pressure in the bomb chamber. The pore was ignited by means of an electrically heated nichrome spiral. In this series of experiments, we

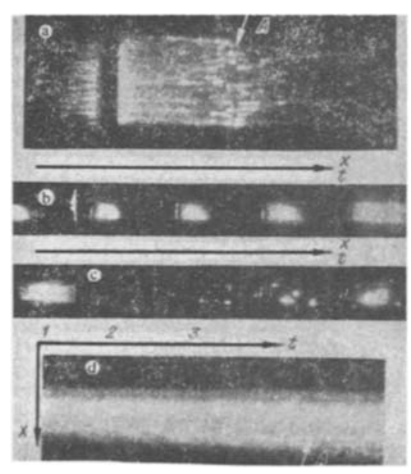

Fig. 2. Frame photographs of the penetration of combustion into a pore (a,b) and anomalous pore combustion (c) (1—completed ignition; 2—total extinction in time $t < 2 \cdot 10^{-4}$ sec; 3—occurrence of new ignition centers after $4 \cdot 10^{-3}$ sec); d) record of penetration of combustion into a pore obtained with a photorecorder (A is the ignition front).

optically recorded the process of flame propagation along the pore, registered the pressure in the bomb chamber, and measured the temperature in the pore by means of thin (30 μ) tungsten-rhenium thermocouples.

The temperature measurements were made by the method developed by Zenin [6].

It should be emphasized that the causes of migration of the products into the pores in the manometric and constant-pressure bombs (when the pores are filled with nitrogen) are essentially different [5].

As the experimental materials we used secondary explosives, nitroglycerine powder, and mixtures based on ammonium perchlorate. For these we determined the critical values of the pore width b_{cr}, for which the penetration of combustion is still possible. It was shown that the relation between b_{cr} and the pressure at which penetration of combustion into the pore is observed is satisfactorily described by an equation of the form $b_{cr} \cdot p = \text{const}$.

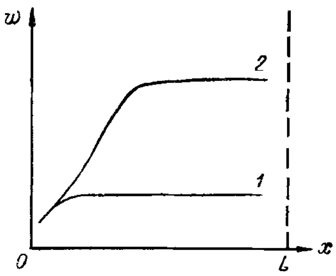

Fig. 3. Schematic representation of the variation of ignition rate w along the length of a closed (1) and an open (2) pore.

In the experiments whose results are discussed below the initial pore width b_0 exceeded the critical width b_{cr}, which ensured the penetration of combustion into the pore. The external pressure in the bomb chamber p_0 did not usually exceed 100 atm.

The migration of gaseous combustion products into the pore leads to the development of an exothermic reaction. It was shown that under our experimental conditions the most typical results of the action of the penetrating products is ignition of the pore surface.

The pore ignition condition can be obtained by equating the amount of heat introduced into the pore by the combustion products to the heat supply needed to create a sufficiently deep heated layer in the condensed phase which can heat the surface of the pore to a temperature at which intense gasification of the explosive begins.

A rigorous theoretical examination of the problem involves serious difficulties, since the ignition of the pore depends on a broad range of gasdynamic and

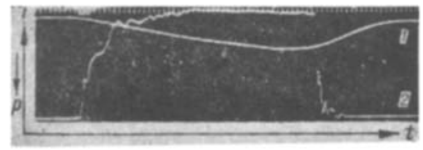

Fig. 4. Record of the pore temperature T(t) (b_0 = 0.1 mm) for nitroglycerine powder (1) and record of the pressure in the bomb chamber (2).

thermophysical parameters and on the physicochemical properties of the burning material. A specific feature of pore ignition is the nonconstancy, with respect to the coordinate and time, of the convective heat flux and the pressure at which ignition occurs.

Depending on the gas flow conditions, the pore size, and the properties of the explosives, the penetrating gases may be products of complete combustion or intermediate products [4, 7]. It should also be stressed that the laws of convective ignition of explosives and propellants are still almost uninvestigated.

Pore ignition was studied as a function of the experimental conditions, the geometry of the pore, and the pressure in the bomb chamber. It was established that the ignition rates may vary within very broad limits from centimeters to hundreds of meters per second.

The use of optical methods (Fig. 2a, b, d) made it possible to establish that a weaker luminescence is registered ahead of the ignition front. This is due to the more rapid motion of the combustion products, which heat the material and are thereby cooled. The ignition front separates the products moving along the pore from the flux flowing out of the pore. This flow pattern can be traced by introducing metal particles into the explosive (Fig. 2a, d).

Results of measuring the ignition rate w along the length of a closed and an open pore, obtained in a con-

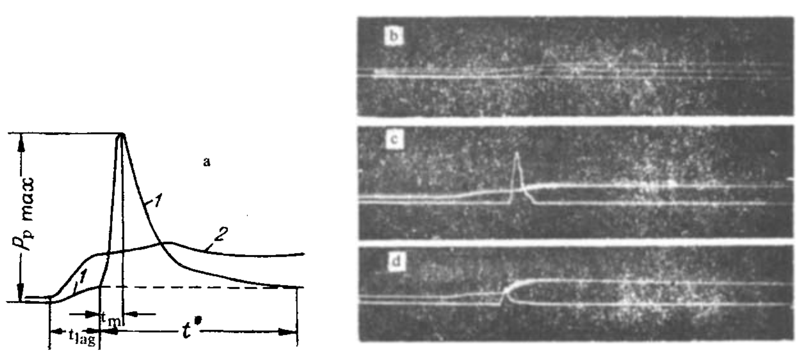

Fig. 5. Schematic representation (a) and oscillograms (b, c, d) of the pressure (1) in a pore with a closed bottom end and (2) in the bomb chamber. The sensitivity of the sensor in the pore was less than that of the sensor in the chamber.

stant-pressure bomb, are presented schematically in Fig. 3. Below, the effect of the initial pore width b_0 on the ignition rate is illustrated for a closed pore:

b_0, mm	0.6	0.4	0.2
w, m/sec	55	100	300
p_{pmax},atm	300	700	1800

As the width of the pore decreases, the ignition rate increases, as noted in [8]. It has also been established that increasing the depth of the pore has the same effect as decreasing its width.*

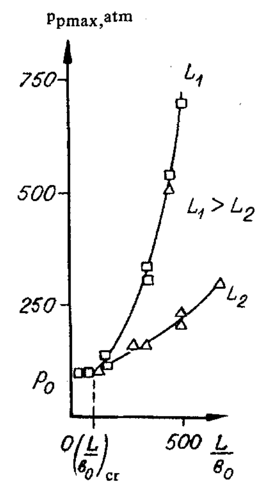

Fig. 6. Maximum pressure in the undeformed pore as a function of the parameter L/b_0.

In a narrow pore with an equivalent hydraulic diameter on the order of 10^{-1}–10^{-2} mm, which is close to the mean pore size ($m \simeq 0.5$), combustion may propagate at a high rate, on the order of hundreds of meters per second, which is almost constant along the length. This may explain the nature of the high-speed regimes propagating at almost constant velocity that occur after the ignition of porous explosives in closed vessels.

Experiments conducted at different pressures in a manometric bomb have shown that as the pressure p_0 increases, the ignition rate also experiences a substantial increase:

p_0, atm	10	100
w, msec	0.2	100
p_{pmax},atm	10	400

Under certain conditions the combustion in the pore is unstable and anomalous, which is expressed in the form of multiple ignition of the pore with subsequent extinction (see Fig. 2c). Anomalous combustion is observed at small external pressures close to atmospheric. Reignition (after extinction) proceeds either as a result of the subsequent propagation of the front or as a result of the development of combustion from individual points. The latter case is characteristic for mixtures based on ammonium perchlorate and indicates the important role of the processes taking place after extinction in the condensed phase.

Anomalous pore combustion may be explained on the basis of the conclusions of [10] relating to the combustion of a propellant in a semiclosed space, since the ignited pore is a flow nozzle (more exactly, a combination of a flow and a thermal nozzle) with a very small free volume. In the same paper it was shown that under critical flow conditions, when the relaxation time of the chamber is much less than the relaxation time of the heated layer, i.e., at low pressures, combustion in a chamber with a small free volume will be unstable, anomalous.

Another possible reason for anomalous combustion is the impossibility of stable combustion in a narrow pore when there is no active (leading) combustion zone. A factor facilitating the breakthrough of combustion into the pores is the small distance h_m from the surface to the high-temperature gas zone [3, 5]. This explains why, in the case of a composite system, combustion penetrates into the same pores at pressures less than in the case of substances with a large h_m (for example, nitroglycerine powder) and at high velocities. For composite systems h_m is an order smaller than for nitroglycerine powder [6, 11, 12].

Measurements of the temperature in the pores of nitroglycerine powder with $b_0 < 2h_m$ have shown (Fig. 4) that in the initial moment after penetration the temperature in the pore is quite low (~1000° K) and increases as the pore burns. In the initial stage the combustion of the powder in the pore is flameless and up to a value $b_0 \simeq 2h_m$ proceeds at a velocity less than the normal burning rate [13].*

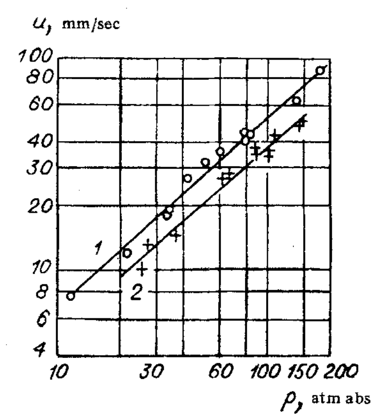

Fig. 7. Pressure dependence of erosive burning rate in a sonic flow. 1) Composite system; 2) nitroglycerine powder.

*In [9] it was shown that increasing the height of the charge facilitates the penetration of combustion into the pores.

*In this series of experiments the pore geometry was such that the pressure in the pore during combustion was almost equal to the external pressure in the bomb chamber.

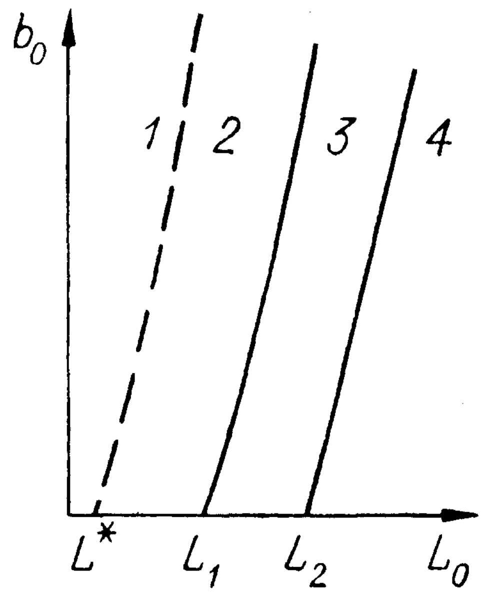

Fig. 8. Diagram illustrating the possibility of pore growth due to the action of excess pressure (the scale along the ordinate axis has been stretched as compared with the axis of abscissas): 1) region of absolute (mechanical) stability; 2) region of practical stability in which the burning pore is not observed to grow during the experiment; 3) region of limited growth, where the development of the pore, starting from a low rate, ceases as a result of the fall in pressure; 4) region of self-sustaining (unlimited) growth, where the pressure is maintained owing to the increase in the depth of the pore.

In the case of composite systems even in narrow pores ($b_0 \simeq 0.1$ mm) and at lower pressures, the temperature in the pore reaches its maximum value almost immediately.

We now consider the consequences of the penetration of combustion into a pore.

It is easy to show that ignition of the pore at a rate much exceeding the surface burning rate must lead to an excess pressure $\Delta p = p_p - p_0$, in the pore which has been experimentally confirmed.* The pressure in the undeformed pore is a function of the following principal dimensionless parameters:

$$p_p = f\left(\frac{w}{u^*}, \frac{b}{h_m}, \frac{L}{b}, z, \frac{x}{L}\right), \tag{1}$$

where u* is the pore burning rate; b is the pore width; z is a coefficient taking into account the resistance to the outflowing products; and x is a coordinate reckoned from the inlet part of the pore.

The first two parameters in expression (1) are related to the process of ignition; the others are associated with the geometric dimensions of the pore and the state of its surfaces.

Figure 5 gives a schematic representation and oscillograms of the pressure in a pore with a closed end and in the bomb chamber. It is clear from the figure that, in a time on the order of $10^{-3}-10^{-4}$ sec after the beginning of the pressure increase in the chamber, equalization of the pressure in the pore begins as a result of the penetration of combustion products. The break in the $p_p(t)$ curve after time t_{lag} corresponds to the beginning of pore ignition.

During the time t_{ig} the pressure in the pore increases, reaching a maximum, after which it falls as a result of the burning of the pore and its mechanical destruction. An increased ($\Delta p \neq 0$) pressure exists in the pore for $(1-50)\cdot 10^{-3}$ sec. Simultaneous optical registration of the process and measurement of the pressure in the pore showed that, in the case of narrow pores, the quantities t_{lag} and t_{ig} are, respectively, the ignition lag and the pore ignition time.

It has been established that all the factors that lead to an increase in ignition rate also tend to increase the pressure in the pore.

The increase in pore pressure was investigated as a function of the parameter L/b_0, which is essentially the ratio of the burning surface to the area of the clear cross section (Pobedonostsev parameter).

Some of the results obtained for a composite system are presented in Fig. 6. As may be seen from the graph, as L/b_0 increases (b_0 decreases while L = = const), starting from a certain critical value $(L/b_0)_{cr}$, there is a progressive increase in pressure in the pore. This is not a case of simple geometric similarity: in pores with the same geometry, the pressure increases with increase in depth, which is associated with a difference in the ignition rates of geometrically similar pores. Of course, the increase in the pressure in the pore as its width decreases cannot continue indefinitely and is limited by the possibility of penetration of combustion into very narrow pores.

When nitroglycerine powder burns [15], the greater part (up to 70%) is dispersed. This and the considerable extent of the low-temperature gas zones [6, 11] are the principal factors leading to the absence of excess pressure in the ignited pore at low pressures in the bomb chamber. In this connection, it should be noted that the convective combustion of porous specimens of nitroglycerine powder is relatively "quiescent" (nonexplosive).

The presence of excess pressure in the pore and a flow of gaseous products causes an increase in burning rate. A feature of the erosive burning of the pore is the presence of high gas flow velocities (up to the sonic level) and large pressures. And, as special experiments have shown, the erosive burning of propellants in a sonic flow is characterized by a strong pressure dependence (Fig. 7):

$$u^* \sim p^{0.8} \tag{2}$$

irrespective of the value of the exponent ν in the normal burning rate law $u = ap^{\nu}$. This dependence can be obtained theoretically starting from the relation between the Nusselt and Reynolds numbers describing heat transfer in a turbulent gas flow [16].

In the presence of a considerable increase in the pressure in the pore, mechanical destruction of the pore walls, leading to an intense increase in the pressure in the bomb chamber (upper curve in Fig. 5d), is observed.

Under the experimental conditions described the most typical result of the action of the combustion products penetrating into the pore is ignition of the explosive. Of course, this does not exclude other possible forms of thermal action such as thermal explosion of the gases filling the pore or heating of the gas as a result of adiabatic compression [17].

We will consider the factors that make penetration of combustion into the pore impossible or substantially reduce the rate of ignition. From the results presented in [3, 5] it follows that the formation of a continuous molten layer at the combustion surface stabilizes the combustion of porous gas-permeable systems. Stabilization by a molten layer is effective in the case of narrow pores, which cannot be ignited as a result of penetration of the gaseous products and burning melt. Moreover, the preliminary filling of the pores with cold gas also considerably increases the combustion stability. Under the conditions of the "walled-in charge" model, this effect may occur when the penetrating gases are sufficiently cold and, being incapable of igniting the explosive, equalize the pressure in the pores and the chamber. This case is observed in the combustion of specimens containing shallow closed pores and systems characterized by a low combustion temperature

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*It should be noted that, on the basis of an analysis of specimens of Kisnemskii powder quenched after the firing of a gun, Serebryakov [14] has shown that an excess pressure may exist in narrow channels.

or extensive temperature zones in the gas phase.

The combustion of mechanically weak porous systems and systems lacking a strong casing may be stabilized as a result of the ejection of material, which prevents an increase in pressure in the pores of the charge [9]. The compression of an easily deformed porous specimen by the pressure at which combustion takes place may lead to the narrowing of the pores to values $b_0 < b_{cr}$, so that penetration of combustion into the pores becomes impossible. In the experiments described above this possibility was excluded.

In conclusion we will consider the case of the burning of an isolated pore in a semi-infinite space when the pore undergoes deformation and increases in depth. One of the reasons for the growth of the pore is the excess pressure associated with the penetration of combustion. We calculated the increase in pressure in the pore with allowance for its deformation and experimentally investigated the growth of the pore during combustion.

The results show that short duration of the excess pressure combined with a low rate of pore growth considerably broadens the region of stable pores as compared with the mechanical calculation (Fig. 8).

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