CONTRIBUTION TO THE THEORY OF THERMAL INTERACTION BETWEEN THE POWDER COMBUSTION ZONE AND THE POWDER-METAL CONTACT

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A method is proposed in [1] for studying experimentally the conditions for powder extinction, in which thermal interaction between the combustion front and the metal-powder contact is used for creating extinction conditions in the combustion zone (method of "freezing" the combustion zone). Cylindrical powder samples with Plexiglas-coated lateral surfaces, placed on a massive copper plate, were burned in the experiment. The powder was ignited at the free end face of the sample. Since at the moment of ignition the distance between the combustion zone and the surface of the metal-powder contact is much greater than the characteristic thickness of the thermal layer in the powder, the cooling effect of the metal (high thermal conductivity) has almost no effect on the combustion process during the initial burning phase, so that the burning process becomes almost stationary shortly after ignition. As the combustion front approaches the metal-powder contact, the influence of the (high) thermal conductivity of the metal on the conditions in the combustion zone continues to increase. Heat removal from the combustion zone increases, the temperature gradient at the surface of the k-phase increases, the combustion conditions become non-stationary, the burning rate changes, and extinction occurs at a certain distance from the contact. On the copper plate there remains a layer of unburned powder, whose thickness depends on the initial temperature of the powder and on the gas pressure within the volume in which combustion occurs. In a series of experiments performed with powder samples with the same initial temperature, it was established that the pressure dependence of the thickness of the unburned powder layer can be described by the formula

\[ \ln h = A - \nu \ln p \]  

where \( h \) is the thickness of the powder residue, \( p \) is the pressure, \( A \) is an experimental constant, and \( \nu \) is an experimental constant equal to the exponent in the power-law relation between the stationary burning rate and pressure.

The theory underlying the empirical relation (1) is proposed below. The experimental conditions are such that the propagation of the combustion front over the powder can be safely considered to be one-dimensional. An idealized picture of the mutual position of the combustion front and the metal-powder contact is shown schematically in the figure. The combustion front moves from the direction of positive values of \( x \).

The surface of the metal-powder contact coincides with the plane \( x=0 \) in such a way that the region \( x<0 \) is occupied by the metal, and the region \( 0<x<x_s \) by the powder. The heat conductivity of the metal is assumed to be large (infinite in the limiting case) compared to that of the powder. In the limiting case, the temperature of the contact surface may be assumed to have a constant value equal to that of the initial temperature \( T_0 \). (To justify this assumption, the volume of the metal disk must be sufficiently large; otherwise, the total heating of the disk should be taken into account.)

We formulate the problem of unsteady burning of a flat layer of powder. The variation of the powder temperature \( T(x, t) \) is described by the
where \( x, t \) are a coordinate and time, respectively; \( \kappa \) is the thermal conductivity coefficient; and \( x_s(t) \) is the coordinate of the powder surface which varies due to the propagation of the combustion front. Initial and boundary conditions must be obtained for Eq. (2). In virtue of the adopted hypothesis about a high thermal conductivity and high integral specific heat of the metal disk, the condition of constant temperature

\[
z = 0, \quad T = T_0
\]

must be fulfilled at any moment of time at the metal-powder contact.

The boundary condition at the burning surface \( x = x_s(t) \) depends on the type of combustion model adopted.

We assume that powder combustion is described by Ya. B. Zel'dovich's theory \([2]\), and also that the temperature at the burning powder surface remains constant during the entire combustion process

\[
x = x_s(t), \quad T = T_s.
\]

The velocity of motion of the burning surface is equal to the burning rate \( u(t) \);

\[
\frac{dx_s}{dt} = -u.
\]

As in \([2]\), we assume that the burning rate under nonstationary conditions depends on the pressure and temperature gradient at the burning surface inside the powder and that this dependence is the same for nonstationary and stationary conditions.

With this assumption, the derivation of an explicit expression for the nonstationary burning rate \( u(x, p) \) must be based on a stationary dependence of the burning rate on the pressure and initial temperature (e.g., an empirical dependence) and also on a nonstationary relation between the burning rate and the temperature gradient at the burning surface. An empirical dependence of the burning rate of powder on pressure and initial temperature usually can be represented in the form

\[
u_0(p, T_0) = \nu(T_0) u_{0p}^p,
\]

where \( u_0 \) is the burning rate of powder under stationary conditions, \( T_0 \) is the initial temperature, \( p \) is the pressure, \( \nu \) and \( u_{1p} \) are experimental constants, and \( \nu(T_0) \) is a known function which may be given, for example, in graphical form.

The temperature gradient at the burning surface under stationary burning conditions is related to the burning rate by the formula

\[
\varphi = \frac{\delta T}{\delta x} = \frac{u_0}{\kappa} (T_s - T_0).
\]

After eliminating \( T_0 \) in (6) and (7), we get a dependence of the burning rate on the temperature gradient at the burning surface and on pressure, which holds also for nonstationary conditions

\[
u(x, p) = \nu(\varphi) \frac{x p}{\nu_0} u_{1p}^p.
\]

From Eqs. (5) and (8) it follows that under nonstationary conditions at constant pressure, the time dependence of the displacement rate of the moving boundary, \( x_s \), is defined by the dependence of the temperature gradient \( \varphi \) at the burning surface of the powder.

The temperature gradient at the burning surface varies during the combustion process but cannot exceed a certain critical value \( \varphi^* \), which represents the maximum value of the gradient observed under