Comments on "Theory of Steady-State Burning of Gas-Permeable Propellants"

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In most cases gas-penetrative burning of porous propellants is an intermediate stage of the deflagration to detonation transition and results in burning velocities tens and hundreds times greater than those for normal conductive combustion. According to the existing models[2,3] the mechanism of gas-penetrative (or convective) burning implies penetration of hot combustion products through the ignition front into the pores of unheated propellant and its successive ignition. This penetration is due to the pressure gradients generated in the reaction zone. If gas-permeability of propellant is high enough the convective heat transfer becomes much more effective than the normal thermal conduction. This explains the high velocities of convective burning. Under most experimental conditions, the burning of porous propellants appears to be an accelerating process because of growing pressure. Kuo and Summerfield have considered the one-dimensional model of the steady-state combustion wave propagation in porous propellants.[1] The authors assumed the combustion wave propagation to be steady state if the pressure at the hot end of the reaction zone is maintained at the constant level.

However, the mechanism considered in Ref. 1 is not adequate, and it can be shown that under the proposed condition the combustion wave with penetration of hot gases through the ignition front will always be unsteady.

In accordance with the mechanism of convective burning, heating, and ignition of propellant grains is caused by the penetration of hot combustion products into the pores of cold propellant. This means that gases at the ignition front move faster than the front itself. The ignition front of the steady-state combustion wave moves at a constant speed. Thus the hot combustion products penetrating through the ignition front and carrying the heat from the reaction zone to the cold propellant will permanently accumulate ahead of the front, acting as a piston on the gases initially contained in the pores. The region ahead of the reaction zone (with pressure exceeding the initial value) will grow in size with time. That is why the one-dimensional steady-state distribution of parameters of the gas flow in the case of gas penetrative burning appears to be impossible.

This conclusion corresponds to the general statement that the particle velocity in a one-dimensional deflagration or detonation wave can not exceed the velocity of the wave itself.[3] For the steady-state burning of gas-permeable propellants, this statement can be justified if one considers the mass conservation equation. For a two-phase medium consisting of the flowing gas and the propellant grains at rest, this equation written in the coordinate system traveling at the same velocity as the combustion wave is

$$\phi\rho_g(V-u)+(1-\phi)\rho_s V=\phi_o\rho_{go}V+(1-\phi_o)\rho_{so}V \quad (1)$$

Where ϕ, ρ_g, and u are porosity, gas density, and velocity averaged over the cross section, respectively, V=velocity of the combustion wave, ρ_s= propellant grain density (the latter is assumed to be constant, i.e., $\rho_s=\rho_{so}$). Subscript "o" denotes the state at the cold end of the combustion wave (in unreacted propellant). Gas velocity at the cold end is zero.

Equation (1) is transformed into

$$(u-V)/V=-[(\phi-\phi_o)\rho_s+\phi_o\rho_{go}]/\phi\rho_g \quad (2)$$

Prior to ignition $\phi=\phi_o$, in the reaction zone $\phi_o<\phi\leq 1$. At any point the right hand side of Eq. (2) is negative, and hence the gas velocity is less than V.

Thus for the one-dimensional steady-state process, gases cannot overtake the ignition front.§ This means that the convective heat transfer in the strictly steady-state plane combustion wave becomes impossible, and pressure constancy is not a sufficient condition for the combustion wave to propagate at constant velocity.

Steady-state convective burning may be obtained if one takes into account the possibility of two-or three-dimensional recirculative flows returning the gas from pores back to the reaction zone or providing a properly distributed mass sink in the unreacted propellant. These flows may be due to the nonuniform distribution of gas-permeability over the propellant cross section. Since the pressure at the hot end is constant, it is more likely that burning of gas-permeable propellant will be decelerating or pulsating.

It follows therefore that in the case considered in Ref. 1, propellant preheating is due to a different mechanism than convective heat transfer. An alternative mechanism can be deduced by analyzing the energy conservation law. In Ref. 1, the work of viscous forces and thermal conduction in gas were considered to be negligibly small. Since the gas does not overtake the ignition front, the only mechanism of propellant preheating which remains is heat transfer from the gases initially contained in pores and heated by compression.

Moreover, the system of steady-state equations which governs burning of gas-permeable propellants[1] has a nonavoidable singularity when $\rho_{go}=0$ (condition of vacuum in pores at the cold end; see Eq. (2) at $\phi=\phi_o$). This confirms the conclusion that the process is determined by preheating caused by compression of the gas contained in the pores. The gas-penetrative heat transfer equations should not have any singularity in the case of vacuum in the pores.

Unlike convective heat transfer, preheating (caused by compression of gas) requires higher pressure, and its effectiveness is less. That is why the calculations made in Ref. 1 resulted in values of pressure (for a given level of burning rates) one order higher than those observed experimentally.[2]

Thus, steady-state burning of gas-permeable propellants, as described in Ref. 1, might exist only under very special conditions for a high pressure burning is accompanied by a viscous flow of the condensed phase which causes the pores to close.

References

[1] Kuo, K. K. and Summerfield, M., "Theory of Steady-State Burning of Gas-Permeable Propellants," *AIAA Journal*, Vol. 12, Jan. 1974, pp. 49-55.

[2] Belyaev, A. Ph., Bobolev, V. K., Korotkov, A. I., Sulimov, A. A., and Chuiko, S. V., "Perekhod Goreniya Kondensirovannykh Sistem vo vzryv," *Izdatel'stvo "Nauka,"* 1973, Moskva, USSR, pp. 111-143.

[3] Shchelkin, K. J. and Troshin, Ya.K., "Gasodinamika goreniya," *Izdatel'stvo Akademii Nauk USSR*, Moskva, 1963, p. 15.

§Even if one accounts for partial condensation or absorption of the combustion products in cold pores, the conclusion remains true.

Received January 23, 1975.
Index categories: Combustion in Heterogenous Media; Combustion Stability, Ignition, and Detonation.

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