Technical Comments

Comments on "Surface Exotherm Reaction during Ignition of Ammonium Perchlorate Propellants"

J. PANTOFLÍČEK* AND F. LÉBR†
University of Chemical Technology, Pardubice, Czechoslovakia

Nomenclature

c = specific heat of propellant
k = $\lambda/\rho \cdot c$ = thermal diffusivity of propellant
p = critical negative gradient of temperature on the surface inside propellant
q_{in} = total heat of ignition
q_e = heat accumulated in the condensed phase of propellant at stable burning
T_{in} = ignition temperature
T_s = surface temperature of propellant
T_0 = temperature of propellant before ignition
u = burning rate
x = distance from the propellant surface
λ = thermal conductivity
φ = absorbed energy flux
φ_K = critical energy flux
τ = ignition exposure time
τ_K = critical ignition exposure time
ρ = density of propellant

IN an interesting Technical Note,[1] Fishman presents results of experimental observations on solid-propellant ignition using the arc-image furnace technique. In our work based on ignition by hot wire[2] similar results were found. Go no-go experiments and determination of the 50% limit of ignition were used in both the works for the determination of the exposure time as a function of the ignition energy flux (or total heat of ignition).

Results published by Fishman can be explained assuming that the ignition takes place when minimal surface temperature T_{in} is attained with inherent heating of the solid propellant to certain minimal depth.[2,6] At a certain surface temperature of the solid propellant, the depth of the heating is the greater, the smaller is the temperature gradient inside the solid propellant. In order to achieve the minimal depth of heating, the negative temperature gradient in the solid propellant on its surface must be smaller than the critical value $p = 1/tg\ \alpha$ (Figs. 1 and 2). Then it can be supposed that p is in agreement with the negative temperature gradient on its surface at steady burning. That means that it must, at the same time, comply with

$$T_s = T_{\text{in}} \tag{1}$$

and

$$-(\partial T/\partial x)_s < p \tag{2}$$

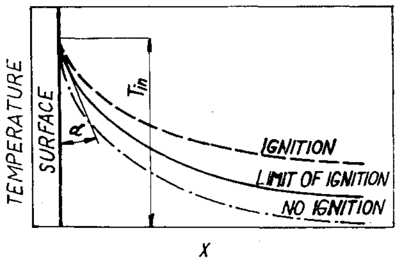

Fig. 1 Temperature profile when ignition temperature on the surface is reached.

For relatively small ignition fluxes, i.e., for[3]

$$\varphi < \lambda \cdot p = \varphi_K \tag{3}$$

$$\tau > (\pi/4k) \cdot (T_{\text{in}} - T_0)^2/p^2 = \tau_K \tag{4}$$

the condition (2) is always satisfied whenever the surface temperature T_{in} is achieved. The ignition depends then only on the surface temperature. The exposure time is then[3] the time necessary to achieve the surface temperature T_{in};

$$\tau = (\pi \cdot \lambda^2/4k)[(T_{\text{in}} - T_0)^2/\varphi^2] \tag{5}$$

In this case, characterized as an extended ignition, the slope $\log\tau = f(\log\varphi)$ equals -2 and the ignition time does not depend upon pressure. Extended ignition is in agreement with the theory of Hicks.[4,5]

At higher ignition energy fluxes, so that

$$\varphi > \varphi_K \tag{6}$$

$$\tau < \tau_K \tag{7}$$

we speak about minimal ignition. At the moment when the ignition temperature is attained on the surface of the propellant, the temperature gradient

$$-(dT/dx)_s > p \tag{8}$$

At minimal ignition the propellant is heated to an insufficient depth (Fig. 2). If the energy flux were interrupted when T_{in} is reached, the propellant would not be ignited. For a successful ignition, the time must be extended and the surface temperature must exceed T_{in}. The onset of exothermic reaction is a result of the increase of the surface temperature over T_{in}.

It is further supposed[2] that the total heat of ignition is the heat that is necessary for a simultaneous achievement, on the surface of the propellant, of both the temperature T_{in} and the temperature gradient $-p$, i.e.,

$$q_{\text{in}} = \varphi_K \tau_K = \frac{\pi}{4} \frac{\lambda}{k} \frac{(T_s - T_0)^2}{p} \tag{9}$$

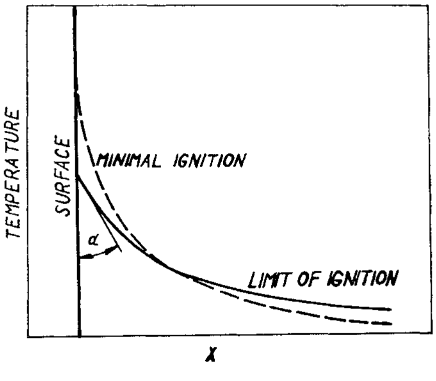

Fig. 2 Temperature profile at minimal ignition.

Received December 20, 1967; revision received March 20, 1968.

* Professor.

† Assistant Professor.

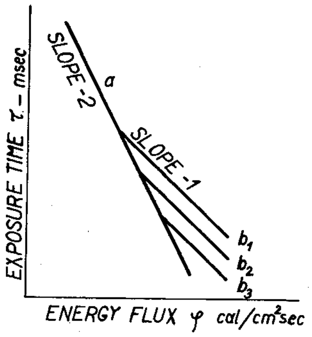

Fig. 3 Ignition characteristics of propellant.

there must be, at minimal ignition,

$$\tau = q_{\text{in}}/\varphi \qquad (10)$$

In the region of minimal ignition, the slope of the line $\log\tau = f(\log\varphi)$ must, therefore, equal -1. Because at minimal ignition the temperature of the surface is higher than T_{in}, surface exotherm must appear.

Up to the present time, we have supposed that the energy flux supplied to the propellant surface is thoroughly used for heating up the solid phase of the propellant and that no liquid interlayer is produced, the formation and heating of which would require certain energy. In case of the formation of the liquid layer, a part of the energy is used for its formation and heating. This fact, however, does not change basic conclusions and results only in the fact that the slopes of the function $\log\tau = f(\log\varphi)$ will not be exactly -2 and -1, but will somewhat differ from these values. Besides that, the values of φ_K and τ_K will change as well. If the thickness of the liquid layer is dependent upon pressure, extended ignition also depends upon pressure to the degree to which heat, accumulated in the liquid layer, is a function of pressure.

It is further supposed that at minimal ignition the total heat needed for ignition q_{in} equals the enthalpy of the wave of combustion in the condensed phase at a stable flame;

$$q_{\text{in}} = (\lambda/u)(T_s - T_0) + q_e \qquad (11)$$

The first member represents the enthalpy of the solid phase and the second the heat accumulated in the liquid phase of the burning propellant. Minimal ignition heat is dependent on the rate of burning in the steady state. As the velocity of burning of propellant usually depends upon pressure, the exposure time, also, will depend upon pressure as far as minimal ignition is concerned.

The dependence of exposure time as a function of heat flux consists of two different parts (Fig. 3), and in logarithmic coordinates it can be represented using a straight line a and a set of lines $b_1, b_2 \ldots b_n$, depending upon the rate of steady burning. Slope -2 is in correspondence with extended ignition and the straight line a is common to all pressures if excess enthalpy does not depend on pressure. Straights $b_1, b_2 \ldots b_n$ correspond to minimal ignition with the -1 slope. To each pressure belongs other straight $b_1, b_2 \ldots b_n$, depending upon the rate of stable burning of propellants. As with increasing pressure the rate of stable burning increases as well, the straights b are shifted, in agreement with increasing pressure, towards the left.

On the previous assumption, it is then easy to explain the dependences observed. At the same time, it is shown that the indication of ignition by means of appearing flame (or increased conductivity or pressure) is not very reliable. Flame can only serve as a proof of surface decomposition which, however, need not be stable in the case of a propellant not warmed up to a sufficient depth.

References

[1] Fishman N., "Surface Exotherm during Ignition of Ammonium Perchlorate Propellants," *AIAA Journal*, Vol. 5, No. 8, Aug. 1967, pp. 1500–1501.

[2] Pantoflíček, J. and Lébr, F., "Ignition of Propellants," *Combustion and Flame*, Vol. 11, No. 6, Dec. 1967, pp. 464–470.

[3] Carslaw, H. S. and Jaeger, J. C., *Conduction of Heat in Solids*, 2nd ed., Clarendon Press, Oxford, p. 75.

[4] Fraser, J. H. and Hicks, B. L., "Thermal Theory of Ignition of Solid Propellants," *Journal of Physical and Colloid Chemistry*, Vol. 54, 1950, pp. 872–876.

[5] Hicks, B. L., "Theory of Ignition Considered as a Thermal Reaction," *Journal of Chemical Physics*, Vol. 22, No. 3, 1954, pp. 414–429.

[6] Librovich, V. B., "Propellants and Explosives," *Zhurnal Prikladnoi Mekhaniki i Tekhniceskoi Fiziki*, No. 6, 1963, pp. 74–79.

Reply by Author to J. Pantoflíček and F. Lébr

Norman Fishman*
Stanford Research Institute, Menlo Park, Calif.

It is gratifying that the work reported by Pantoflíček and Lébr confirms my previous observations. Their explanation of the results involving the surface temperature gradient and the relationships between "extended ignition" (pressure-independent regime) and "minimal ignition" (pressure-dependent regime) are consistent with my views of an ignition model. Furthermore, essentially the same model has been suggested by von Elbe.[1]

However, I question the validity of the authors' suggestion that the $\log\tau$-$\log\varphi$ relationship in the region of minimal ignition is expressed by a line of slope equal to -1. Although much of my data do approximate such a relationship, some data appear to tend toward a zero slope relationship as the incident flux becomes increasingly larger than the critical flux. Perhaps such deviation from the behavior predicted by the authors can be accounted for by adequate treatment of the surface-coupled exotherm and the ablative-type endothermic reactions which might also be involved at the higher energy fluxes.

Reference

[1] von Elbe, G., "Solid Propellant Ignition and Response of Combustion to Pressure Transients," *Aerospace Engineering 1966, The Proceedings of a Conference Held at the University of Maryland, March 15, 1966*, edited by J. A. Schetz, AFOSR 66-1943, Sept. 1966, Air Force Office of Scientific Research, pp. 50–73.

Received February 1, 1968.

* Chairman, Polymer Technology Department. Associate Fellow AIAA.

Comment on "Forces on Spheres inside Diffusers"

Fred W. Schmidt* and George S. Springer†
University of Michigan, Ann Arbor, Mich.

In Ref. 1, the authors presented a relationship between the force coefficient and the Reynolds number for spheres placed inside diffusers. This relationship was obtained by

---

Received April 1, 1968.

*Graduate Student, Fluid Dynamics Laboratory, Mechanical Engineering Department; also Engineer, Ford Motor Co.

† Associate Professor, Fluid Dynamics Laboratory, Mechanical Engineering Department. Member AIAA.