References

[1] Williams, M L, "Surface singularities resulting from various boundary conditions in angular corners of plates under bending," *Proceedings of the 1st U S National Congress of Appl Mechanics* (American Society of Mechanical Engineers, New York, 1952), pp 325–329

[2] Morley, L S D, "Bending of a simply supported rhombic plate under uniform normal loading," Quart J Mech Appl Math 15, 413–426 (1962)

[3] Conway, H D, "The approximate analysis of certain boundary value problems," J Appl Mech 27, 275–277 (1960)

[4] Conway, H D, ' The bending, buckling, and flexural vibration of simply supported polygonal plates by point matching," J Appl Mech 28, 288–291 (1961)

[5] Conway, H D, "Triangular plates analyzed by point-matching," J Appl Mech 29, 755–756 (1962)

Deflagration Characteristics of Ammonium Perchlorate Strands

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A new ammonium perchlorate deflagration model is presented which characterizes the passage of a deflagration wave through a monopropellant strand as being the result of the propagation of a continuous ignition front A two-step series mechanism was assumed for the deflagration process, the first stage being an initiation reaction at a particle surface, which is then followed by the actual burning of a particle The deflagration model describes semiquantitatively the burning rate of ammonium perchlorate as a function of pressure (700–1400 psi), temperature, particle size, and strand density

Introduction

THE linear regression rate of a solid propellant depends upon a number of complex physical processes Decomposition, which starts within the solid in some cases, attains completion in the gas phase at some distance from the surface Since the chemical reactions are extremely fast, particularly at the high pressures of rocket chambers, direct experimental investigation of the burning process presents a formidable problem

An examination of ammonium perchlorate deflagration shows that the burning behavior of the pure oxidizer is a reasonable approximation of the basic behavior of typical solid propellants containing this oxidizer, with regard to the level of both burning rate and pressure exponent This indicates that the deflagration behavior of pure ammonium perchlorate has a predominant influence on the deflagration characteristics of propellants employing it Consequently, a complete understanding of the over-all mechanism of ignition and deflagration for ammonium perchlorate is paramount for an understanding of steady-state combustion processes occurring in ammonium perchlorate-based composite propellants

Although some insight into the mechanism of ammonium perchlorate deflagration has been achieved,[1–3] direct application of this information has proved inadequate to describe quantitatively the steady-state combustion processes occurring in ammonium perchlorate composite propellants Two important and related points, which should serve as guidelines for future fundamental efforts in this area, emerged from a review of the previous investigations

The first is the desirability of working with the simplest possible system Even the simplest system, e g ammonium perchlorate, involves complex interactions among several physical processes The second is the need to understand the kinetic mechanism of the combustion phenomena The kinetic mechanism is by far the least understood of the interacting processes, as the presence of the other processes tends to mask kinetic factors Since rate expressions and boundary conditions are integral parts of any model of the combustion phenomenon, the kinetic information is paramount to the development of more accurate models of the combustion process

Received October 17, 1963 Deflagration model was developed in a thesis submitted in partial fulfillment of the requirements for the doctor of philosophy degree in chemical engineering at the University of California, Berkeley, California

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Ammonium Perchlorate Deflagration Model

The deflagration model presented here was developed from an original concept that the burning velocity, on a particle scale basis, fluctuated and could be considered constant only over sufficiently long distances The velocity variation was thought to have a period of approximately d/u, that is, initiation must take place at each individual particle [4]

The ammonium perchlorate monopropellant strand is considered to be composed of an array of individually distinguishable spherical particles Over-all strand deflagration is assumed to occur by a mechanism involving repeated individual particle initiations and burning processes On a particle basis, deflagration proceeds by a two step series mechanism, the first step being particle initiation that is then followed by the actual particle-burning stage As a preceding particle in the strand burns away, a subsequent particle is exposed to a hot, reactive gaseous environment of temperature T_F (gas flame temperature) Energy is transferred from this hot gaseous environment, and ignition occurs when the surface temperature attains a critical value (i e , auto ignition temperature) A stable flame position will be quickly established above the particle, and the particle will then burn at a constant velocity characteristic of the ambient pressure and temperature conditions

To derive a relationship for the total time τ required for the deflagration wave to pass through a particle, characteristic times are associated with the individual initiation and burning steps comprising the series process The total time is defined by

$$\tau = t_i + t_b \tag{1}$$

where t_i is the particle-initiation time and t_b is the particle-burning time The development of an expression for the ignition time is founded on the concept that the surface layers of the ammonium perchlorate particle must attain a certain temperature (i e , auto-ignition temperature) before ignition will occur Differential thermal analysis studies indicate that the auto-ignition temperature of ammonium perchlorate is about 350°C in the absence of catalysts Initiation is assumed to be dependent only upon the net heat flux at the particle surface, and the mass of the particle consumed during the ignition phase is considered to be negligible

From the solution of the equation describing the heating of a sphere by an external heat flux, the following relation for the ignition time is obtained:

$$t_i \propto (d^{0.8}/F_0) \tag{2}$$

where d is the particle diameter, and F_0 is the heat flux

Figure 1 schematically represents the interaction of the various processes as the burning front approaches a particle An approximate analysis of the complex interplay of the various unit processes during the initiation step indicated that

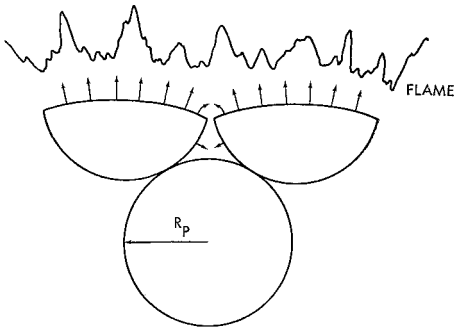

Fig 1 Schematic of particle initiation process

the effective initiation flux varied inversely with particle diameter Equation (2) can then be written in the form

$$t_i = kd^{1.8} \tag{3}$$

Once the combustion of the particle has been initiated, it is assumed that the particle burns at a constant linear rate The particle-burning time can thus be defined by

$$t_b = k_1 d \tag{4}$$

Substituting Eqs (3) and (4) into (1), the total time is then given by

$$\tau = kd^{1.8} + k_1 d \tag{5}$$

The experimentally observed burning velocity is defined as

$$v_a = d/\tau \tag{6}$$

Replacing τ by Eq (5) and rearranging to show particle size dependence more clearly, Eq (6) becomes

$$1/v_a = kd^{0.8} + k_1 \tag{7}$$

An analytical expression for k_1 can be obtained from an approximate solution[4] of the energy equation describing the over-all deflagration process

In terms of the proposed model, the first term on the right in Eq (7) shows the influence of the initiation process on the observed burning rate, whereas the second term is the actual particle-burning velocity independent of initiation factors If the foregoing relationship is indeed capable of representing the experimental data, a family of curves with pressure as a parameter would result at each initial solid temperature

Figures 2 and 3 show the experimental data obtained in Ref 4 plotted in the form indicated by Eq (7) A Crawford strand burner with hot wire ignition was used to obtain the experimental data The solid lines in Figs 2 and 3 were obtained by applying the technique of least mean squares to the experimental data It is apparent that the burning rate can be

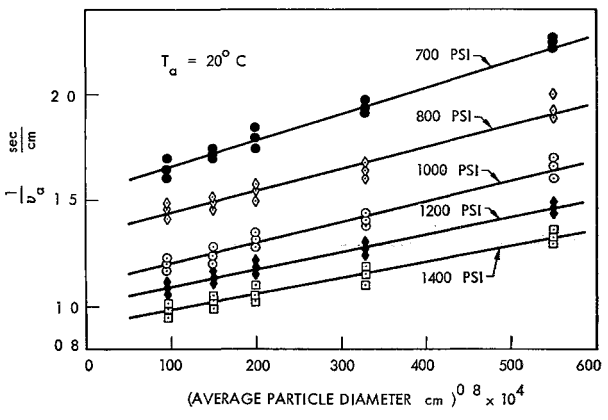

Fig 2 Strand burning rate as function of particle size—20°C

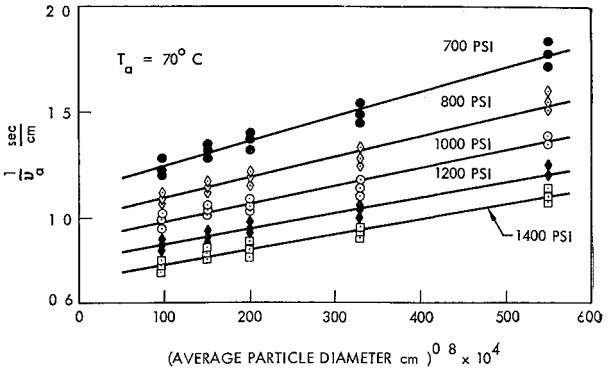

Fig 3 Strand burning rate as function of particle size—70°C

adequately correlated, in the particle-size range studied in this investigation, by the use of Eq (7)

The ability of the model to describe the effects of particle size, pressure, and strand density on the burning rate lends support to the idea that the deflagration of ammonium perchlorate strands can be characterized as being the result of the propagation of a continuous ignition front In addition, the model clearly indicates the direction for future work in this area In order to develop a quantitative description of ammonium perchlorate deflagration, the several unit mechanisms occurring must be investigated in greater detail Specifically, the more important unknown areas requiring study are the nature and magnitude of the kinetic reaction processes associated with the particle-ignition phenomena and the burning rate of the individual particles

References

[1] Bircumshaw, L L and Newman, B H, "The thermal decomposition of ammonium perchlorate," Proc Roy Soc (London) **A227**, 115–132 (1954); **A227**, 228–241 (1955)

[2] Friedman, R and Levy, J B, "Research on solid-propellant combustion," Atlantic Res Final TR, Air Force Office Sci Res 2005 (1961)

[3] Arden, E A, Powling, J, and Smith, W A W, "Observations on the burning of ammonium perchlorate," Combust Flame **6**, 21–33 (1962)

[4] Shannon, L J, "Effects of particle size and initial solid temperature on the deflagration rate of ammonium perchlorate strands," Ph D Thesis, Univ Calif (1963)

Heat Transfer from Nonequilibrium Ionized Argon Gas

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THE effect of ionization on boundary-layer flow and heat transfer has been a matter of considerable argument in recent years, for, apart from the scarcity of experimental data, a discrepancy was found between the result obtained by Scala and Warren[1] and those by others which are summarized in Refs 2 and 3 In the present work, the effect of ionization on heat transfer is investigated for argon flow both theoretically and experimentally

The transport properties of argon used for the calculation is that of Penski,[4] in which the transport properties are determined using the Chapman-Enskog method from the available data on electron scattering intensity The electron-

Received October 18, 1963
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