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Review of Solid-Propellant Ignition Studies

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Abstract

AN extensive review of the literature on solid-propellant ignition was made to establish the state-of-the-art. Various ignition theories, experimental measurements, and ignition criteria were critically examined. The review was summarized in easy-to-read tabular form to facilitate comparison between various studies. The effects of important parameters on ignition processes were also discussed. Major technological gaps were identified and areas for future studies recommended.

Contents

The study of the ignition processes of solid propellants is important for many combustion and propulsion applications. An extensive review of research work performed in this area was conducted 14 years ago by Price et al.[1] Because many ignition studies have been conducted in the interim, a detailed survey of literature subsequent to the review paper of Price et al.[1] is presented by the authors in Ref. 2. This synoptic of Ref. 2 (in which over 100 publications are cited) brings together the developments to date and the difficulties encountered under a unified view in order to establish the state-of-the-art in solid-propellant ignition.

In general, ignition of a solid propellant is a complex phenomenon which involves many physicochemical processes, as depicted in Fig. 1. The ignition consists of the following sequence of events: 1) energy transfer to the propellant by an external stimulus which can be thermal, chemical, or mechanical; 2) heating and subsequent decomposition of the solid phase; 3) diffusion of vaporized gases into the surrounding atmosphere; and 4) subsurface, heterogeneous, and/or gas-phase reactions. When the net heat evolved from chemical reactions overcomes heat losses, sustained ignition is achieved. It is generally understood that ignition is incomplete if steady-state combustion does not follow the ignition event after the removal of external energy stimulus.

The time period from the start of external stimulus to the instant of sustained ignition is called ignition delay. Generally, it is controlled by three characteristic time intervals, viz., inert heating time, mixing (diffusion plus convection) time, and reaction time. Ignition delay, however, is not simply the algebraic sum of these three characteristic time intervals since there is no clear demarcation between the mixing process and the chemical reactions; these processes may have some overlapping periods. Ignition delay is one of the most important parameters in the study of ignition. However, it is very difficult to identify precisely the instant of sustained ignition.

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Following the review of Price et al.,[1] ignition theories are classified into three major groups: 1) gas-phase ignition theory; 2) heterogeneous ignition theory; and 3) solid-phase ignition theory. The gas-phase ignition theory considers the ignition process to be controlled by the chemical reaction between vaporized fuel-rich and oxidizer-rich mixtures and ambient oxidizer gases. In the heterogeneous ignition theory, the reaction between the solid-phase fuel and ambient oxidizer at the interface is viewed as the controlling mechanism. The solid-phase ignition theory does not consider heat release and mass diffusion in the gas phase; rather, the temperature rise inside a solid propellant is achieved by the heat release caused by subsurface chemical reaction and/or external heating from the surroundings.

In each of the three major theories described above, several models have been proposed. These models differ in the governing equations considered, assumptions made, interfacial conditions imposed, ignition criteria used, and types of propellants studied. In order to facilitate a detailed comparison between various models, a complete set of governing equations and boundary conditions, together with the physical meaning of each term in the formulation, is given in the full paper.[2]

Selection of a "proper" ignition criterion is probably the most controversial issue in ignition study. Up to the present, there has been no universally acceptable definition of the ignition criterion. This is probably due to the fact that ignition depends not only on the mode of energy deposition onto the solid propellant, but also on propellant characteristics and ambient conditions. Since calculated as well as observed values of ignition delay depend on the choice of an ignition criterion, conclusions drawn from comparisons of theory and experiments are also affected by the particular, although somewhat arbitrary, choice of an ignition criterion. In the

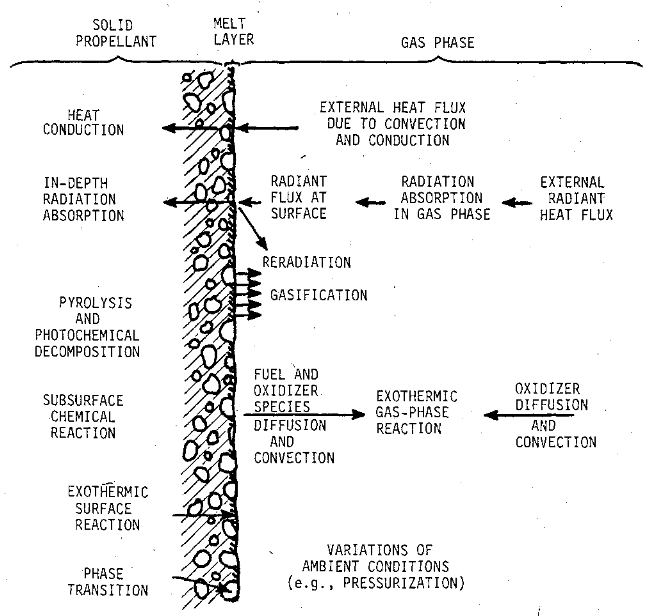

Fig. 1 Physical processes involved in solid-propellant ignition.

reviewed literature, 14 different ignition criteria in theoretical models and 6 different ignition criteria in experimental studies were identified.[2] In gas-phase models, the ignition criterion is generally based on variations in gas-phase temperature or reaction rate distributions, whereas in heterogeneous and solid-phase models the ignition criterion is usually based on the attainment of a critical temperature or a critical rate of temperature increase at the propellant surface. The most commonly used ignition criteria in experimental studies are the first detection of flame or the go/no-go test. The desired characteristics of ignition criteria are: 1) compatibility in experimental and theoretical studies, and 2) relative insensitivity of ignition delay to specific constants employed by the ignition criteria to simulate the runaway condition.

Most of the important experimental studies and gas-phase, solid-phase, and heterogeneous models are summarized in separate tables in Ref. 2. For each investigation, the tables include reference source, basic assumptions, theoretical formulation, ignition criterion, results, and review comments. Test setup and measurement techniques used in the experimental studies are also included.

In the gas-phase ignition theory, most models (except that proposed by Kumar and Hermance[3]) are one-dimensional. The gas-phase theory is usually more complicated than the solid-phase or heterogeneous ignition theory because gas-phase species and energy equations must be included in the formulation. The major advantage of the gas-phase theory is its capability to predict dependence of ignition delay on such ambient conditions as oxidizer concentration, pressure, etc. In composite propellants whose fuel binder ablation temperature is considerably lower than that of the oxidizer particles, the fuel may react with the ambient oxidizer before any significant decomposition of the solid-phase oxidizer occurs. Under such circumstances, the gas-phase ignition theory is more realistic.

Compared with gas- and solid-phase theories, much less attention has been given to heterogeneous ignition theory, probably because the ignition process in the usual rocket motor does not depend chiefly on a rate-controlling heterogeneous reaction. A majority of the models proposed in this theory use asymptotic methods to obtain solutions. The heterogeneous ignition theory is also called hypergolic when the surface reaction begins immediately following the introduction of reactive fluids at room temperature. The hypergolic ignition theory also differs from the gas- or solid-phase theories in terms of the external heat flux, which could be absent in the hypergolic situation but is required in the case of the other two.

Mathematical formulation of the solid-phase theory is greatly simplified since gas-phase equations are not considered. Thus, the solid-phase theory generally cannot predict the effect of conditions in the surrounding atmosphere. However, under conditions of low external heat flux, high ambient oxidizer concentration, and high pressure, the inert heating time is much longer than the diffusion or chemical reaction time; the ignition delay predicted by the solid-phase theory may agree closely with experimental observations.

The actual ignition process of solid propellants is, in general, too complex to be described by any one gas-phase, solid-phase, or heterogeneous theory under all operating conditions. It is desirable, therefore, to develop a theory which allows simultaneous reactions in the gas phase, solid phase, and at the interface, and which also employs an ignition criterion that is flexible enough to allow a runaway condition at any site. Such an effort has been attempted by Bradley[4] and the authors[5]; these studies are still in progress and only limited results have been published.

The major difficulties encountered in a theoretical analysis of solid-propellant ignition include: selection of an appropriate reaction mechanism for the propellant under specific operating conditions; detailed specification of chemical kinetics of the precombustion reactions; nonavailability of adequate thermal, chemical, and transport property data; multidimensionality of the ignition process resulting from the heterogeneous nature of the propellant; and the selection of the ignition criterion. In addition, the numerical solution of the model is intricate and cumbersome.

The experimental study of ignition is just as complex as the theory. Adequate simulation of the ignition process in a rocket motor in a laboratory is one of the major difficulties encountered in solid-propellant ignition studies. The actual igniter generates hot gases and particles flowing over or impinging upon a solid propellant surface, whereas most of the laboratory experiments use idealized methods of energy transfer which cannot fully simulate the actual process. In addition, the time period of the entire ignition event is very short (several hundreds of microseconds to a few milliseconds for many commonly used solid propellants under normal conditions) and the region of major activity is extremely small (usually in the order of several hundred micrometers). Thus, because it is difficult to probe and observe the ignition region, no broad experimental data base is as yet available.

It is usually observed that the ignition delay decreases[2] with an increasing rate of external energy transfer to the propellant, ambient pressure, ambient oxidizer concentration, gas-to-solid density or thermal conductivity ratio, ambient pressurization rate, exothermic chemical reaction rates, and initial temperature of the propellant or surrounding gas. An increase in the oxidizer particle size decreases the ignition delay. In general, the types of fuel binders, oxidizers, catalysts, opacifiers, and burning rate modifiers used (together with their relative mass fractions) and have some effect on ignition delay.

Conclusions

As demonstrated by this review, an enormous amount of work has been done in the area of solid-propellant ignition. Qualitative (and in some cases quantitative) predictions for the ignition delay and its dependence on several parameters can be made by adjusting various constants and by making a priori assumptions about the controlling mechanism. However, these predictions are somewhat semiempirical, and a significant amount of research in this area is needed to obtain more extensive data accurately and systematically for comparisons with theory. Overall, although the foundation for solid propellant ignition research is laid, ignition studies are still far from complete.

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