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for

INVESTIGATION OF THE STARTING TRANSIENTS OF HIGH PERFORMANCE SOLID-PROPELLANT MOTORS

Conducted Under NASA Grant NGR 31-001-109
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DESCRIPTION OF RESEARCH PROGRAM

The initial studies under the grant (from 1967 to 1969) produced significant progress in the investigation of the fundamental processes that occur during the starting transient period of solid propellant motors with low loading densities and small length-to-diameter ratios. The program of research culminated in an investigation of the processes, which occur during the starting transients of high performance solid propellant motors. This is the practical class of motors which have high loading densities, large length-to-diameter ratios, and low port-to-throat area ratios.

The purposes of this program was to obtain better understanding of the starting transients of solid propellant motors and to develop design principles for the prediction of the transients in high performance igniter and motor configurations. Concurrently, basic research and diagnosis were conducted on the processes affecting ignition transients such as heat flux to the propellant, propellant response to the igniter stimulus, flame spreading over the propellant surface and nonsteady combustion gas dynamics of the entire motor.

The program consisted of the following parts:

1) Development of theoretical models for the starting transient of solid propellant motors.
2) Design and manufacture of instrumented rocket motors equipped with transparent windows, heat flux gauges, pressure transudcers, etc.

3) Diagnostic experiments to determine such items as the flame spread rate, ignition delay times, flow patterns, erosive burning rates and heat flux distribution.

4) Revision of theoretical models based on results of diagnostic experiments.

5) Establishment of prediction and design rules.

6) Rocket motor firings to compare the predicted pressure transients with the actual pressure transients.

7) Quantitative analysis and interpretation of the firing records of service rocket engines to the extent that they were available, for the purpose of testing the applicability of the design rules derived from the program.

8) As a separate topic, investigation of the restart transients of hybrid rocket motors.

SUMMARY OF RESEARCH RESULTS

During the seven year period that includes 1967 and 1974 the results of our research on solid propellant rocket motor ignition and propulsion related topics were described in reports and technical papers. These publications form a set of self-consistent sources on the broad topic of solid rocket motor ignition. This section contains abstracts of the publications.

The publications summarized in this document are the technical reports and papers which have been archived by the appropriate libraries and agencies. Some types of publications (i.e., preprints of papers later published in journals, progress reports which were superseded by final reports, administrative summary reports which merely summarize publications listed in this document, and informal presentation summaries) have not been included if the results reported in them are also contained in a more comprehensive archive publication. It should be noted that the interplay among the publications is great since there has been a commonality of propellants, fuels, rocket motors, data reduction techniques, etc. throughout our investigations.

"THRUST TRANSIENT PREDICTION AND CONTROL OF SOLID ROCKET ENGINES"

W. J. Most, B. W. MacDonald, P. L. Stang and M. Summerfield

WSCI Paper 68-33, The Combustion Institute, October 1968.

The research reported in this paper is directed toward the development of an analytical model for predicting the thrust-time curve during the entire ignition transient of a solid propellant motor. This model characterizes the local ignition event by a constant critical surface ignition temperature and by including a surface heat release term to account for exothermic decomposition below the critical temperature. Flame spreading is described by coupling this ignition model with an empirical description of the gas phase heat convection to the propellant grain. The propellant burning rate after ignition is achieved is taken as the steady state burning rate. The model is completed by writing the dynamic energy and continuity equations. This model is compared to others appearing in the literature.

The theoretical predictions of the model are compared to experimental test firings of a two-dimensional rocket motor and of motors with more realistic grain configurations. An extensive range of igniter system and engine design parameters are covered. Both aluminized and unaluminized propellants are considered and shown to be similar. The abrupt shift from a vigorous, well-ignited rocket motor to an extended hangfire or misfire can be caused by small changes in igniter design parameters. This sensitivity is predicted theoretically and demonstrated experimentally.

This paper concludes that a physically rational theory has been developed that can predict the entire motor ignition transient for motors with head-end pyrogen igniters. This is verified experimentally.

Based on work performed under NASA Grant NGR-31-001-109 supervised by Langley Research Center.

Accession No. A69-18365*# - Available from AIAA.

"STARTING THRUST TRANSIENTS OF SOLID ROCKET ENGINES"

W. J. Most and M. Summerfield

Aerospace and Mechanical Sciences Report No. 873, July 1969,
Princeton University, Princeton, N.J.

In the past, the design engineer has been forced to rely on empirical and statistical knowledge of previous firings in order to design the ignition system of a solid rocket motor or to predict the starting delay time of a given rocket-igniter system. In order to predict the entire ignition transient analytically, the processes of local ignition, heat transfer and subsequent flame propagation and the gas dynamics of the combustion chamber must all be described quantitatively. Each of these elements has been the focus of extensive research in itself. The purpose of this paper is to present the results of these research efforts, in our laboratory and elsewhere, in relation to the objective of predicting analytically the entire ignition transient.

A particular analytical model, developed for the class of engines with large port-to-throat area ratios and head-end mounted pyrogen igniters, is presented. This model characterizes the local ignition event by ascribing to the propellant a critical surface temperature for ignition and by including a surface heat release term to account for exothermic decomposition while the surface is still below the critical temperature. Flame spreading is described by coupling this ignition model with a general description of the heat transfer from the gas phase to the unignited propellant grain. Any propellant burning rate law, steady or nonsteady, can be used once ignition has been achieved. The model is completed by the dynamic energy and continuity equations for the motor free volume. This particular model is compared to others which have appeared in the literature, with special attention paid to those reports in which comparisons between theoretical predictions and experimental test firings are offered.

The limitations of the various models are examined, especially with regard to those particular assumptions which cannot be justified experimentally. The applicability of the various models for the prediction of marginal (hangfire) situations is examined.

This paper concludes that the analytical models now available can provide useful predictions of the entire ignition transient, at least for the class of motors for which they have been developed, and this has been verified experimentally.

Based on work performed under Grant NGR 31-001-109 sponsored by the Office of Advanced Research and Technology, NASA, supervised by Langley Research Center.

Accession No. N72-75433 - Available from NTIS.

"COMBUSTION ANOMALIES IN STOP-RESTART FIRING OF HYBRID ROCKET ENGINES"

M. A. Saraniero, L. H. Caveny and M. Summerfield

Aerospace and Mechanical Science Report No. 945, Sept. 1970, Princeton University, Princeton, N.J.

An experimental investigation of the restart process of an oxygen-Plexiglas hybrid rocket demonstrated that preheating the fuel (as a consequence of a previous ignition and a temporary extinguishment) significantly increases the rate of chamber pressurization and produces regression rate overshoots during reignition. Higher rates of chamber pressurization measured during the restart transient imply faster instantaneous regression rates of the fuel during restart. Transient periods following the initial ignition and the restart after a two-second shut-down were observed for four experimental tests which were conducted at two oxidizer flow rates, 0.078 lbm/sec and 0.039 lbm/sec, and two chamber pressures, 80 psig and 320 psig. Thermocouples made from 0.001 inch diameter chromelalumel wire were embedded in the fuel to record subsurface temperature histories.

A mathematical model of the thermal processes in the fuel and the events that occur during an experimental firing was developed to calculate the regression rate transients. Quantitative agreement with experimental results was obtained by making nominal corrections to the calculated convective and radiative heating rates. A parametric study investigated the influence of the fuel's thermal characteristics (thermal conductivity, surface temperature, and heat of gasification) and the shut-down duration on the transient responses. The calculated results showed that instantaneous regression rate overshoots were as high as 29% when high energy fuels are reignited.

The results of this study indicate that the transient behaviors of pressure and regression rate during reignition after shut-down (the duration of which has been varied over a range of 0.9 to 4.0 sec) can be anticipated and predicted once the regression characteristics of individual fuel/oxidizer combinations have been established. Thus, extensive experimental firings of full scale rocket motors will not be required to adequately predict pressure-time histories and fuel consumption following reignition if proper attention is given to understanding the thermal distributions during shut-down periods.

Based on work performed under Contract NGR-31-001-109 issued by Office of Advanced Research and Technology, NASA.

Accession No. N72-26960 - Available from NTIS.

"RESTART TRANSIENTS OF HYBRID ROCKET ENGINES"

M. A. Saraniero, L. H. Caveny and M. Summerfield

Journal of Spacecraft and Rockets, Vol. 10, No. 3, March 1973, pp 215-217.

The problems associated with restarting hybrid rocket motors (i.e., rocket motors wherein a liquid or gaseous oxidizer is injected into the port of a solid fuel grain with subsequent mixing and combustion of the oxidizer and fuel) following a brief period of extinguishment were investigated experimentally. In the extreme, reignition and re-establishment of the oxidizer flow of a briefly extinguished hybrid motor which is heated in depth and undergoing subsurface reactions will produce catastrophic increases in burning rate. If a precise p_{ch} vs t program is required, results demonstrate that the designer must carefully program the external ignition stimulus and oxidizer flow rate during the restart ignition period by taking into consideration at least three factors: (1) pressure prior to extinguishment, (2) duration of shutdown interval, and (3) desired pressure following restart. The measured pressure vs time traces explicitly show the extent to which restart ignition differs from the first ignition. Increasing $\dot{m}_O$ greatly reduces the t_9 on reignition. The time to achieve 90% of the operating pressure t_9 is reduced by as much as 88%, and the time to achieve ignition is reduced by as much as 45%. Also the measured pressure time traces reveal that there is no appreciable increase in burning rate after the thermal profile is fully established. This indicates that the specific energy (approximately 350 cal/g) required to gasify PMM is much larger than the specific energy increase attributed to indepth absorption of thermal radiation (30 cal/g) during the time interval of the test.

Based on work performed under sponsorship by NASA's Office of Advanced Research and Technology under Grant NGL-31-001-109 and monitored by the Applied Rocket Research Section of the NASA Langley Research Center.

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"THE STARTING TRANSIENT OF SOLID-PROPELLANT ROCKET MOTORS WITH HIGH INTERNAL GAS VELOCITIES"

A. Peretz, L. H. Caveny, K. K. Kuo and M. Summerfield

Aerospace and Mechanical Science Report No. 1100, April 1973, Princeton University, Princeton, N.J.

A comprehensive analytical model which considers time and space development of the flow field in solid propellant rocket motors with high volumetric loading density is described. The gas dynamics in the motor chamber is governed by a set of hyperbolic partial differential equations, that are coupled with the ignition and flame spreading events, and with the axial variation of mass addition. The flame spreading rate is calculated by successive heating-to-ignition along the propellant surface. Experimental diagnostic studies have been performed with a rectangular window motor (50 cm grain length, 5 cm burning perimeter and 1 cm hydraulic port diameter), using a controllable head-end gaseous igniter. Tests were conducted with AP composite propellant at port-to-throat area ratios of 2.0, 1.5, 1.2, and 1.06, and head-end pressures from 35 to 70 atm. Calculated pressure transients and flame spreading rates are in very good agreement with those measured in the experimental system.

Based on work performed under Research Grant NGL-31-001-109 sponsored by the Office of Advanced Research and Technology, NASA.

To be cataloged by NTIS.

"THRUST TRANSIENTS OF LARGE SOLID ROCKET MOTORS"

Leonard H. Caveny, Arie Peretz and Martin Summerfield

Proceedings of the 10th JANNAF Combustion Meeting, Aug. 1973 at Newport, R. I. CPIA Pub. 243, Vol. I, Dec. 1974, pp. 21-44.

An analytical model which considers time and space development of the flow field in solid-propellant rocket motors with high volumetric loading density was used to predict the ignition characteristics of larger solid rocket motors (e.g., thrust > 2×10^6 lb and length > 100 ft). Uncertainties associated with the prediction of peak pressures are attributed largely to incomplete knowledge of erosive burning. The calculated results demonstrate that the flow field from large solid propellant motor grains overpower the uncertainties associated with the detailed ignition processes. Sensitivity analyses revealed that the ignition and pressurization times were not appreciably affected by the expected variations in motor parameters, if the pyrogen produced sufficiently high convective heating rates. Accordingly, small (< 0.1% of total motor weight) head-end mounted pyrogens which promote a rapid onset of flame spreading are expected to produce rapid and reproducible chamber pressurization.

Based on work performed under NASA Grant NGL 31-001-109 monitored by NASA Langley Research Center and the Jet Propulsion Laboratory of the California Institute of Technology.

Available only from CPIA.

"THE STARTING TRANSIENT OF SOLID PROPELLANT ROCKET MOTORS WITH HIGH INTERNAL GAS VELOCITIES"

A. Peretz, K. K. Kuo, L. H. Caveny and M. Summerfield

AIAA Journal, Vol. 11, No. 12, Dec. 1973, pp. 1719-1727.

A comprehensive analytical model which considers time and space development of the flow field in solid-propellant rocket motors with high volumetric loading density is described. The gas dynamics in the motor chamber is governed by a set of hyperbolic partial differential equations, that are coupled with the ignition and flame spreading events, and with the axial variation of mass addition. The flame spreading rate is calculated by successive heating-to-ignition along the propellant surface. Experimental diagnostic studies have been performed with a rectangular window motor (50 cm grain length, 5 cm burning perimeter and 1 cm hydraulic port diameter), using a controllable head-end gaseous igniter. Tests were conducted with AP composite propellant at port-to-throat area ratios of 2.0, 1.5, 1.2, and 1.06, and head-end pressures from 35 to 70 atm. Calculated pressure transients and flame spreading rates are in very good agreement with those measured in the experimental system.

Based on work performed under NASA Grant NGL-31-001-109 monitored by NASA Langley Research Center and the Jet Propulsion Laboratory of the California Institute of Technology.

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