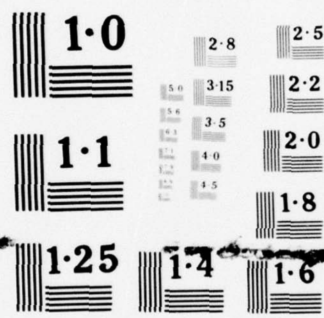
AD-A043 337 PENNSYLVANIA STATE UNIV UNIVERSITY PARK DEPT OF MECH--ETC F/G 19/1
ANALYSIS AND THEORETICAL MODELING OF THE COMBUSTION OF GRANULAR--ETC(U)
JUN 77 K K KUO DAAG29-74-G-0116
UNCLASSIFIED ARO-11731.4-E NL

1 OF 1
ADA
043337

END
DATE
FILMED
9-77
DDC


1·0
2·8
2·5
5·0
3·15
2·2
5·6
3·5
6·3
2·0
4·0
1·1
4·5
1·8
1·25
1·4
1·6

ARO-11731.4-E

(12)

ANALYSIS AND THEORETICAL MODELING OF THE COMBUSTION OF GRANULAR PROPELLANTS, WITH EXPERIMENTAL VERIFICATIONS

FINAL REPORT

Kenneth K. Kuo

June 29, 1977

U.S. Army Research Office

Grant Number DAAG 29-74-G-0116

Department of Mechanical Engineering
The Pennsylvania State University
University Park, PA 16802

APPROVED FOR PUBLIC RELEASE
DISTRIBUTION UNLIMITED

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER	2. GOVT ACCESSION NO.	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) Analysis and Theoretical Modeling of the Combustion of Granular Propellants, with Experimental Verifications		5. TYPE OF REPORT & PERIOD COVERED Feb. 15, 1974 - Feb. 14, 1977
		6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s) Kenneth K. Kuo		8. CONTRACT OR GRANT NUMBER(s) DAAG 29-74-G-0116
9. PERFORMING ORGANIZATION NAME AND ADDRESS Department of Mechanical Engineering The Pennsylvania State University University Park, PA 16802		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS
11. CONTROLLING OFFICE NAME AND ADDRESS U. S. Army Research Office Post Office Box 12211 Research Triangle Park, NC 27709		12. REPORT DATE June 29, 1977
		13. NUMBER OF PAGES 8
14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office) 1. Combustion and Prop. Br. Ballistic Research Lab. Aberdeen Proving Ground Aberdeen, MD 21005	2. Ballistics and Comb. Research Branch Picatinny Arsenal Dover, NJ 07801	15. SECURITY CLASS. (of this report) Unclassified
		15a. DECLASSIFICATION/DOWNGRADING SCHEDULE NA

16. DISTRIBUTION STATEMENT (of this Report)

Approved for public release; distribution unlimited.

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

NA

18. SUPPLEMENTARY NOTES

The findings in this report are not to be construed as an official Department of the Army position, unless so designated by other authorized documents.

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Two-Phase Reacting Flow	Mobile Bed of Gun Powders
Granular Propellants	Gas Penetration
Modeling of Interior Ballistics	Deterrent Effect
Flame Spreading	Vented Chamber Experiments
Accelerated Flame Front	Dynamic Burning of Pellets

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

Gas-permeable propellants possess great potential for producing sizable thrusts within extremely short time intervals. A research program was set up with the objectives: (1) to obtain a deeper understanding of high speed flame propagation and the gas dynamic behavior of two-phase reactive flow systems; and (2) to predict the rates of gasification during transient heterogeneous combustion of granular propellant beds.

DD FORM 1 JAN 73 1473 EDITION OF 1 NOV 65 IS OBSOLETE

Unclassified

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

20. The following transient phenomena occur in a few milliseconds: penetration of hot gases into interstitial voids, convective heating of pellets to ignition, granular bed compaction and rapid pressurization in a thick-walled, steel chamber. Pressure transients and flame-front speeds are measured by high-frequency pressure transducers and ionization probes, respectively. A gaseous pyrogen ignition system utilizing a spark ignition was found most suitable for varying igniter strengths and achieving high reproducibility.

The physio-chemical phenomena described above have been formulated into a theoretical model. The method employed in this study is the gas dynamic approach which is developed by formulating the governing equations on the basis that mass, momentum and energy fluxes are balanced over control volumes occupied separately by the gas and particle-phases. The governing equations were derived in the form of coupled, non-linear, inhomogeneous partial differential equations. This system of equations is solved together with some empirical input such as heat transfer, flow resistance, intergranular stress and the burning rate law. They are found to be of hyperbolic type, since all the eigenvalues are real. The compatibility relations are used as extraneous boundary conditions together with some physical boundary conditions to solve the boundary points. A stable, fast convergent, explicit numerical scheme incorporated with predictor and corrector are used in the interior, and the method of characteristics is used on the boundaries.

The results show that the flame front accelerates significantly and the rate of pressurization increases substantially in the downstream direction. The igniter strength and the propellant gasification temperature were found to have pronounced effects on the pressurization process. The theoretical predictions are in close agreement with the experimental data.

ACKNOWLEDGMENTS

This report represents a summary of the results of the research work performed under Grant No. DAAG 29-74-G-0116 at The Pennsylvania State University, under the supervision of the Engineering Sciences Division of the U.S. Army Research Office at Research Triangle Park, North Carolina. The support of Mr. James J. Murray, Director of Engineering Sciences Division, and of Dr. Austin W. Barrows, Jr., of the Ballistic Research Laboratories is greatly appreciated. Thanks are due to Mr. Norman J. Gerri and Mr. Carl Nelson of BRL for their technical advice in this study.

Special thanks to Mr. J.H. Koo and Mr. G.R. Coates for their assistance in the theoretical formulation and computer programming. The author is also grateful to Mr. T.R. Davis, Mr. T.J. Malmgren, Mr. I.P. Troutman and Mr. W.C. Morris for their experimental efforts on this project. The help of Mrs. P.C. Chang in the numerical solution of the mathematical model is greatly appreciated.

Thanks are also due to Mr. Richard H. Comer of BRL who authorized the supply of granular propellants used in our work; and to Dr. Richard R. Bernecker of NSWC/WOL for providing us with technical information about ionization pins.

INTRODUCTION

Gas-permeable propellants possess great potentials in achieving high-speed combustion and producing sizable thrusts within extremely short time intervals. The work performed in this three-year project was a basic research study on the combustion of gas-permeable propellants enclosed in a cylindrical chamber. The motivation of this research is to achieve a deep understanding of the combustion processes of mobile granular solid propellants.

The overall research objectives were:

1) Anomalous burning behavior has been observed in combustion of granular solid propellants. A better understanding of the transient combustion phenomena is required to reduce hazards and to improve the design of propulsion systems.

2) To advance the state-of-the-art in the combustion of granular propellants by formulating a complete theoretical model describing the important physical phenomena involved in both gaseous and solid phases.

3) To solve the theoretical model by selecting a stable, fast convergent numerical scheme so that effects of (a) igniter strength, (b) propellant physio-chemical characteristic and (c) propellant loading density can be studied.

4) To conduct experimental firings in a thick-walled combustor with a fixed boundary, to measure the pressure-time transients at various axial locations and flame propagation rates so that the theoretical model developed in this study can be verified.

5) To evaluate the effects that a single variable (i.e., igniter strength, propellant composition, and downstream boundary) has on the transient combustion process.

6) To evaluate the importance of the dynamic burning effect in the transient combustion of granular propellants.

Because of the complexity of the overall ignition and combustion processes, early designs of solid propellant gun systems relied largely on trial-and-error procedures. Although considerable progress has been made by researchers in this field, but there are still many problems to be solved, questions to be answered. In order to achieve high reproducibility and to predict the ballistic performance accurately, one must have a thorough understanding of a number of physical phenomena and the coupling relationships between them. Ignition and combustion processes in solid propellant guns generally involve: (1) impact ignition of the primer material, (2) flame spreading inside the igniter or percussion unit, (3) venting of igniter products into the granular solid propellant bed, (4) heating of solid propellant grains to ignition by the hot product gas of the igniter material, (5) penetration of burned gas into the unignited portion of the granular propellant bed, (6) compaction of the granular bed due to pressure gradients, (7) flame spreading inside the granular bed, (8) chamber pressurization before the projectile starts to move, (9) rapid and uneven compression at various portions of the cartridge sometimes with strong shock spikes impinging at the base of the projectile, (10) shot start and pronounced expansion of the bed of burning pellets and (11) friction losses and heat transfer from gaseous product to the gun barrel and projectile.

Most of the phenomena mentioned above have significant effects on the muzzle velocity. In addition to these complicated and interrelated phenomena, there are many other important factors which will influence the performance of a solid propellant gun, such as (a) deterrent concentration inside solid-propellant grains for small arms systems, (b) erosive burning phenomena due to high relative velocities between the gas and the solid particles, (c) deformation and fracture of propellant grains under high pressure and stress conditions, (d) flux output of the primer, (e) geometry of the cartridge chamber, and (f) fluidization condition of the granular bed. All these factors are closely related to the physical phenomena involved in ignition and combustion.

THEORETICAL WORK

To determine the transient gas dynamic behavior of hot-gas penetration, flame propagation, chamber pressurization and expansion processes in the granular propellant bed, the mass, momentum, and energy equations for the gas phase, and the mass and momentum equations for the solid phase are derived and expressed in a quasi-one-dimensional form. They are approached by considering the balance of fluxes over a finite volume small enough to give the desired spatial distributions in the complete system but large enough to contain many solid particles, so that the averaged particle velocity and fractional porosity are meaningful. The control volumes considered in the derivation of the governing equations are those occupied separately by the gas- and particle phases.

Because the transient interval studied is so short, the temperature profile inside the particles has a very steep gradient. Although the average bulk temperature of a solid particle can be obtained, it would not be useful for determining the ignition condition, the speed of flame front propagation and the rate of heat transfer from the gas to solid phase. Instead of treating the solid phase energy equation like the mass and momentum equations for the particles, the transient heat conduction equation is considered, so that the propellant surface temperature and the temperature gradient can be accurately obtained. A simple surface-temperature ignition criterion is also used to describe the burning condition of particles along the propellant bed.

In addition to the above governing equations, the equations of state for gas- and particle-phases must be specified. The co-volume effect becomes important at high pressures, so the Noble-Abel dense gas law is used as the equation of state for the gas phase. The statement of a constant density for the solid-propellant particles serves as the equation of state for the particles.

The initial conditions required to solve the system of equations are the initial distributions of gas temperature, pressure, velocity, particle velocity, propellant surface temperature and fractional porosity. The total number of boundary conditions required depends upon the flow conditions at the primer and projectile end of the propellant bed. To complete the theoretical model, a set of empirical correlations for flow resistance and heat transfer between particles and gas together with the physical properties of the granular propellant are used to solve the system of partial differential equations.

The detailed description and the mathematical formulation of the two-phase granular propellant combustion model developed under this project are given in publications 1 and 2. According to the theoretical calculations, some special features of the combustion process in granular propellants were noted.

(a) The rate of pressurization increases in the downstream direction and the pressure peak developed in the granular bed travels downstream.

(b) The flame spreading rate increases significantly in the downstream direction.

(c) A stronger igniter causes faster flame spreading and also a higher rate of pressurization.

(d) Igniter gas flow compacts the bed and causes the propellant grains to move in the shear disc direction.

(e) As the pressure peak develops in the chamber, the gas and particle respond to the pressure gradient by moving from center toward both ends of the chamber simultaneously.

(f) For tightly packed beds, the particle velocity is significantly lower than the gas velocity before the rupture of shear disc.

The model described in the first two publications does not include the effect of dynamic burning. Before any specific approach was taken in the consideration of this transient burning phenomena, an extensive literature survey of previous works in the field of dynamic burning was conducted. This review work is given in publication No. 3.

Although numerous dynamic burning models for solid propellants have been proposed in the past, few if any were intended to deal with the highly convective fields normally found in confined granular propellant charges. In this work, the rate of convective heat feedback in the presence of surface gasification is expressed in terms of a surface blowing parameter, skin friction coefficient, and local gasdynamic conditions. The transient heat conduction equation, posed for a solid particle in a Lagrangian system, is solved for the thermal profile. The detailed analysis and formulation are given in publication No. 4.

Some important results obtained from our dynamic burning study are listed below:

(a) After using realistic physical inputs from a granular bed model, pronounced burning rate spikes were found to exist for a short period after the onset of ignition.

(b) Pressurization rate is not the sole contributor to the burning-rate phase lag and amplitude of overshoot. Instead, local gasdynamic conditions as well as the thermal profile accrued during the preheat period have been found to be equally important.

(c) The influence of dynamic burning was found to be most significant at lower pressures. For the conditions studied, the duration of the interval in which dynamic burning was prevalent was found to be very brief. Furthermore, after the culmination of each burning rate spike, the burning rate returned asymtotically to the steady-state burning rate.

EXPERIMENTAL WORK

In the experimental work, a thick-walled steel combustion chamber (6 inches in length and 0.306 inch I.D.) has been constructed. A shear disc or projectile forms the stationary or moving downstream boundary, respectively. Pressure transducers and ionization probes are spaced equally along the chamber for measuring both the pressure-time traces at various locations and the flame propagation speed in packed beds of granular propellants. In addition to the conventional primers, a gaseous pyrogen ignition system utilizing hydrogen-oxygen mixtures with a spark ignition source was also used to vary the igniter mass flux and duration.

The effects of igniter strength, propellant type, deterrent concentration, and projectile motion on the overall transient combustion processes in granular propellant beds were studied experimentally. The results show that igniter strength significantly affects the duration of the induction period, and also the accelerative behavior of the pressure front traveling through the bed; a weaker igniter causes a more pronounced pressure front acceleration. A large igniter volume was found to reduce the rate of flame spreading and pressurization processes. Combustion of slightly deterred propellants produced extremely rapid flame spreading, higher peak pressures, and higher pressurization rates than regularly deterred propellants. Propellant particle geometry was found to greatly affect the rate of total mass consumption within a propellant bed and thereby influence the peak pressures and pressure wave phenomena within the bed. The detailed experimental test rig design and the comparison of firing data under different conditions are given in publications 5 and 6.

CONCLUSIONS

An investigation has been conducted for a two-phase, granular propellant combustion problem. Several important conclusions are summarized in the following.

1. Transient wave phenomena and flame spreading have been measured in a thick-walled cylindrical chamber by high frequency transducers and ionization pins. Experimental results indicate that:

   (a) The rate of pressurization increases in the downstream direction and the pressure peak developed in the granular bed travels downstream.

   (b) Under certain conditions, the flame spreading rate increases significantly in the downstream direction.

   (c) A stronger igniter causes faster flame spreading and also a higher rate of pressurization.

2. A successful theoretical model has been developed to describe the combustion of mobile granular propellants. A stable, fast-convergent numerical scheme is used for solving the complete system of equations. The above experimentally observed phenomena were also displayed in the solutions of the theoretical model.

3. The calculated pressure-time traces and flame spreading rates agree closely with the experimental data.

4. Burning rate spikes of large amplitude were obtained in the dynamic burning study. However, due to the extremely short time duration of the spikes, the dynamic burning effect in the overall combustion event in the particular test configuration considered was found to be negligible.

5. In the study of granular bed combustion, there are still many unsolved problems in both theoretical and experimental areas. These problems were identified in a special JANNAF Workshop and deserve to be considered for future studies. A summary of the Workshop is given in publication No. 7.

PUBLICATIONS

1. Kuo, K.K., Koo, J.H., Davis, T.R. and Coates, G.R., "Transient Combustion in Mobile Gas-Permeable Propellants," Acta Astronautica, Vol. 3, pp. 573-591, 1976.

2. Koo, J.H., "Theoretical Modeling and Numerical Solution of Transient Combustion Processes in Mobile Granular Propellant Beds," M.S. Thesis, Mechanical Engineering Department, The Pennsylvania State University, University Park, Pennsylvania, 1975.

3. Kuo, K.K. and Coates, G.R., "Review of Dynamic Burning of Solid Propellants in Gun and Rocket Propulsion Systems," presented at the Sixteenth Symposium (International) on Combustion held at the Massachusetts Institute of Technology, Cambridge, Massachusetts, August 15-20, 1976.

4. Coates, G.R. and Kuo, K.K., "Dynamic Burning Assessment in the Combustion of Mobile Granular Propellants under Intense Forced Convection," Sixth International Colloquium on Gasdynamics of Explosions and Reactive Systems, Stockholm, Sweden, August 22-26, 1977.

5. Davis, T.R., "Experimental Study of Transient Combustion Processes in Granular Propellant Beds," M.S. Thesis, Mechanical Engineering Department, The Pennsylvania State University, University Park, Pennsylvania, 1977.

6. Davis, T.R. and Kuo, K.K., "An Experimental Study of the Transient Combustion Processes in Granular Propellant Beds," AIAA Paper No. 77-854, AIAA/SAE 13th Joint Propulsion Conference, Orlando, Florida, July 11-13, 1977.

7. Kuo, K.K., "A Summary of the JANNAF Workshop on: Theoretical Modeling and Experimental Measurements of the Combustion and Fluid Flow Processes in Gun Propellant Charges," CPIA Pub. 281 of 13th JANNAF Combustion Meeting, Vol. 1, pp. 213 - 233, December 1976.