Ignition Transient Investigation of Rocket Motor

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ABSTRACT

Ignition transient is a very rapid process lasting only in the order of 100 milliseconds and therefore it is difficult to measure all relevant ballistic properties. Numerical simulation is thus useful to quantify some of these hard to measure flow and ballistic properties. One-dimensional model was employed to study the effects of aging using simplified aging scenarios for both N-H sustainer and booster motors. Also the effects of newly designed igniter on the ignition of N-H sustainer was simulated.

Radiation effects could be significant in terms of energy flux increase to the propellant surface and the energy exchange between the combustion gas itself. One dimension implementation of radiation showed significant effects for rear-mounted igniter. Implementation of radiation effects into 2-D axi-symmetric numerical model was completed and its effects on the N-H sustainer were examined.

To have a reliable prediction of computer model on ignition transient, accurate chemical property data on the propellant and igniter gas are required. It was found that such property data on aged N-H motors are not available. Chemical aging model can be used to predict to some degree of accuracy effects of aging on chemical and mechanical properties. Such a model was developed, albeit 2-dimensional, to study migration of moisture through a representative solid rocket motor configuration.

1. INTRODUCTION

1.1 Background

Ignition transient refers to a short period of time following the commencement of igniter firing during which rapid pressure change occurs in the combustion chamber of solid rocket motors. It lasts typically in the order of 10~100 milliseconds and therefore it is difficult to measure ballistic properties.

Solid rocket motors are usually mass-produced and stored in controlled environment before its use. Therefore mechanical and chemical properties of the rocket motor and igniter system can be changed through chemical reactions involving components and moisture in the atmosphere. Rigorous testing of motor component by dissecting deployed motor has been performed and statistical methods are frequently used to assess their service life expectancy.

Nike-Hercules motors were developed in 60's and have been proved to be a very reliable surface to air missile system. To ensure successful firing of these motors, however, mechanical and chemical property testing must be performed frequently. It is also useful to predict its performance using available simulation methods to save time and expenses usually required for actual

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testing of the old motors.

Numerical simulations have become an important tool to analyze complex physical processes in the motor and provide quantitative ballistic data that can be used to improve the performance of existing motors. The purpose of the present research was to develop numerical models and use them to evaluate the aging effects on Nike-Hercules motors and the impacts of new igniter design on the ignition transients of N-H motor.

1.2 Scope of the Investigation

Simulation results for the Nike-Hercules sustainer with the original igniter and with newly designed igniter were performed using 1-D. model and the results are described in chap.2. Radiation effects can be significant for solid rocket motors with aluminum particles since emissivity of aluminum oxide particle can be large. Effect of aluminum particle was examined using 1-D model and extension to 2-D model without two fluids effects was accomplished. Detail of 1-D modification was reported in reference[4] and 2-D model with radiation is described in chap.3. Ultimately, it is required to have accurate property data for aged motor and these data are best obtained by testing actual motors. Additional tool for the aging process is prediction model based on physical process involving motor materials and the moisture in the air. A diffusion model is developed as a first step toward the prediction of aging process. And the results applied to a representative solid rocket are presented in chap.4. Finally, conclusions obtained from the projects and recommendations for the future efforts toward better understanding of propellant aging, reaction process and ignition transients are presented in chap.5.

2. SIMULATION MOTORS

2.1 Numerical Model

Ignition transient model used to simulate N-H motors is the 1-D model described in reference[1,2]. This model employs separate equations for the gas and solid particle phases and IPSA algorithm based on finite volume method was used[3]. Improvements made during the project period on the 1-D model was to include radiation terms and higher order approximation on convective flux terms at the control volume boundaries[4]. One additional modification on the model was to include nozzle efficiency to match the simulation results with the test data. The nozzle efficiency is defined by

$$\eta_{nozzle} = \left(\frac{V_{actual}}{V_{calculated}} \right)^2$$

where velocity is at the exit of the nozzle. The nozzle efficiency is taken to be 0.92[5].

The listing of 1-D model and detail on the input parameters was given in reference[1,2,4] and is not repeated here.

2.2 N-H Sustainer Motor

Input parameters for the N-H sustainer motor were gleaned from Solid Rocket Motor Manual[6] as much as possible. Since the data collected are incomplete considerable extrapolations were needed to obtain all physical and chemical properties for the use of simulation. Table 1 shows the chemical and numerical parameters used in sustainer simulation as was reported in reference[1,2,4].

One of the least known data was the igniter gas flow rate and it was extrapolated using the data from a reference[6]. The resulting mass flow rate is shown in Fig. 1.

Table 1. Chemcial and Numerical Parameters

Igniter gas	**Remarks**
IGTYPE=0 FLIG=0 TEIG=2520 K	Igniter mass flow rate is assumed (see below) Igniter gas temperature is unknown.
combustion gas	
R=344.1 (J/kg.K) GAM=1.21 WEIGHT=24.82 VIS10=9.45e^{-5}N.s/㎡ TK10=2.6e_{-2} W/m.K	Viscosity and conductivity are not important
Aluminum oxide particle	No aluminum oxide particles and all input parameters used for 2-phase were ignored in computation
Solid Propellant	
ROPR=1630 kg/㎥ TPSIG=539 K CPPR=860 J/Kg.K TKPR=0.304 W/m.K TEFREF=2444K WPRM=0 WPRX=2.1 DIGT=0.01 sec IPHASE=1 PREF0=68 atm pressure RREF0=0.8 cm/sec ENREF=0.286 (n in burning rate equation) ALPE=0 (no erosive burning) BETE=125 (not used)	Auto-ignition temperature is unknown. The maximum wetted perimeter ratio is calculated using port geometry. Ignition delay time is assumed. Assumed single phase since no aluminum particles and all parameters used for 2-phase are ignored in computation. In the program, burning rate equation is r=rref(P/Pref)n, where P is in atm pressure and rref is in cm/sec
Initial conditions	
RO1I=1.16 kg/㎥ U1I=0 TE1I=270 - 325K	Stagnant atmospheric air with varying temperatures. No particles and thus no interface interactions.
Geometry	
NPG1S=5 NPG1=NPG2=NPG3=10 NPG4=20 NGT=10 NTE=20 IPLUG=0 PBLOC=0	See Fig.1 for other dimensions including cross sectional area of the port and nozzle. No plug is used for storage.
Numerical parameters	All typical values are used.
Radiation parameters	
INRAD=0 (no radiation)	Radiation effects were neglected since no aluminum particles. All parameters for radiation are neglected in computation.

The major concern of gaged solid rocket motor is the degradation of its mechanical and chemical properties. Mechanical property changes such as decreased structural strength can cause cracks in the propellant resulting in firing failure. Chemical properties of igniter gas and propellant can delay the ignition transient by reduced flame temperature or auto-ignition temperature.

Results of parametric study for several scenarios of aged N-H motors were performed. Table 2 shows the assured property changes used in the simulation.

Table 2. Property Changes Assured in Simulation

Cases	Changes in properties and initial conditions
A	Baseline conditions as described in Table 1.
B	T_{ini} = 270 K (cold weather storage), others are same as for case(a)
C	T_{ini} = 325 K (hot weather storage), others are same as for case(a)
D	TEIG=2016 K (reduced igniter gas temperature by 20%), others as in case(a)
E	Case(b) plus Case(d) (cold weather and reduced igniter gas temperature)
F	Case(c) plus 10% increase in burning surface area (WPRX=2.3) due to cracks.
G	T_{ini} = 288 K, others as in Case(a).

Fig. 2 shows the flame spreading time for 7 cases as shown in Table 1. It is clear form this figure that flame spreading time depends strongly on the time at which the second segment of propellant ignited. Flame spreading time on the remaining propellant is almost simultaneous, and shows very little variation except the third segment for all cases. There is also wide variations between a group (cases a, c and f) and others. Reduced igniter temperature and initially cold propellant temperature increase the flame spreading time considerably. Wide variation of flame spreading time is not a desired ballistic property of solid rocket motors.

2.3 New Igniter Design

To improve the ignition transient of N-H sustainer motor, a new igniter for N-H sustainer motor has been designed. One of the main differences from the original igniter is the increased mass flow rate compared with the original igniter, as shown in Fig. 1. Also igniter gas temperature of the new igniter is 3075 K that is considerably higher than 2520 K used in the original igniter.

The numerical simulation of N-H sustainer using the new igniter has been performed. All input parameters needed for the simulation except noted above are unchanged from the values as shown in Table 1.

Fig. 3 shows the new igniter gas flow-rate. Three cases of ignition transient were simulated; base case (case a) and two cases with initially cold propellant temperature of 270 K (case b) and initially high propellant temperature of 325 K (case c). These scenarios simulate storage conditions in winter and summer.

Fig. 4 shows the pressure and Mach number variation in the motor at the steady state. Like in the original case, distinctive property variations are seen in the chamber, connecting passage and the nozzle sections.

Fig. 5 shows total thrust and head-end pressure variations as a function of time for the base case (case a). Total thrust for the new design is about 14,200 lbf that is slightly higher than the original case of 13,000 lbf.

The maximum head-end pressure gradient 340 psia/10 ms for the new case is also higher than the one for the previous case, 120 psia/10 ms.

Total pressure for three cases show as in previous simulation that initially higher propellant temperature produces higher total thrust and larger head-end pressure gradient (Fig. 6 and 7).

Fig. 8 shows the flame-spreading time with the new igniter. Flame-spreading time is much shorter (16 ms) than the previous case (45 ms) for the base case (case a in both simulations). This is expected since the new igniter mass flow rate is larger and the igniter gas temperature is higher.

The most striking feature of the new igniter performance is that the flame - spreading time changes only slightly with the initial propellant temperature that is lower and higher than the base case. For the original igniter, flame-spreading time changed drastically reaching up to 240 ms. This implies that the new igniter provides more predictable ignition transients and stable performance.

The utility of numerical modeling of ignition transients is the rapid turnaround time for the prediction of new design as demonstrated in this example. The accuracy of simulation results should, however, be checked against experimental data, before making final evaluation. It is therefore strongly recommended that such a comparison should be made in near future as a part of ongoing research project.

3. RADIATION EFFECTS ON IGNITION TRANSIENTS

Radiation is an important mode of heat transfer in high temperature fluid. Radiation effects come into play in two places in ignition transient: increased heat flux to the propellant surface and heat transfer between combustion gases. The first effect increases the net heat flux thus decreases the flame spreading time. The latter effect makes the combustion temperature more uniform and its effects on ignition transient is not a clear cut. Implementation of radiation effects into 2-dimensional axi-symmetric compressible flow code used for ignition transient analyses[8,9] has been completed as a part of present project.

3.1 Implementation of Radiation Effects into 2-D Code

Radiation heat transfer effects are included the ignition transient process as a source term in the energy equation. To resolve this effect, radiation transfer equation must be solved simultaneously with other transport equations. Radiation transfer equation is given by, for each beam direction,

$$\frac{dI^l}{ds} = -\beta I^l + S^l$$

In this expression, β is the extinction coefficient and S^l is the source. Integrating the above equation for a control volume and a control angle, finite volume equation for each beam is obtained.

Once the radiation beam intensity is calculated by the radiation transfer equation via finite volume method, radiation energy contribution in the energy equation can be calculated by

$$-\nabla \cdot \vec{q}_{rad} = -k(4\pi I_b - G)$$

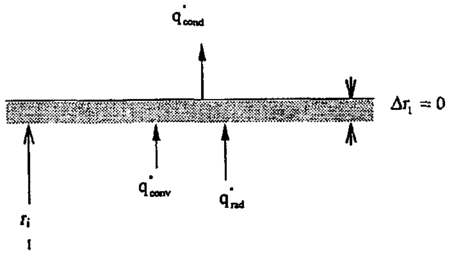
where,

$$I_b = \sigma T_p^4$$

$$G = \int_{4\pi} I^l d\Omega^l$$

In this expression k is the extinction coefficient and σ is the Stephen-Boltzman constant. Radiation energy source term expresses the fact that radiation energy entering a unit volume minus the radiation energy leaving the volume is the net radiation energy contribution for the energy balance. A subroutine RADAXIG is added to 2-D axi-symmetrical compressible code.

Another effect of radiation on the ignition transient is the radiation energy flux to rite propellant surface before the auto-ignition begins. This effect is of course included in the formulation as a boundary condition for the radiation transfer equation. But it also affects the boundary condition for the radial conduction for the propellant before the auto-ignition in the subroutine PRTEMP.



Energy balance at the inner radius of propellant as depicted in the above figure requires that

$$q''_{conv} + q''_{rad} = q''_{cond}$$

The net radiation heat flux to the propellant surface is

$$q''_{rad} = q''_{rad,in} - q''_{rad,out} =$$

$$\sum_l I^l D_r^l - (1-\varepsilon_b)\sum_l I^l D_r^l - \varepsilon_b \sigma T_b^4$$

3.2 Effects of Radiation

It is assumed that the propellant surface is black (ε_b=1.0) and the combustion gas is isotropic with k=0.1 m^{-1} and without scattering (σ=0). Radiation boundary at the head-end and the nozzle exit are also assumed black.

It is expected that the flame spreading time is shorter with radiation because of added energy flux at the propellant surface. Fig. 9 shows the total thrust comparison for two cases. With radiation, thrust builds up little faster than without radiation. Other properties, such as pressure, temperature, Mach number and total energy distribution of steady-state show very little changes with radiation.

Fig. 10 shows the pressure distribution at t=0.1 sec: (a) without radiation and (b) with radiation. The maximum pressure in the chamber was 18.7 atm pressure without radiation and 20.9 atm pressure with radiation. Increased energy flux to the propellant decrease flame spreading time and increases pressure in the chamber. This is similar to the case for the initially elevated propellant temperature without radiation.

Fig. 11 shows Mach number distribution at t=0.1 sec and Fig. 12 shows temperature distribution at the same time. There are very small differences between two gases.

Thus it may be concluded that radiation effects for Nike-Hercules motor are not significant except that flame spreading is little shorter with radiation. This conclusion may not be true for aluminized propellant with high scattering coefficient.

4. CHEMICAL AGING MODEL

Chemical reaction in solid propellant reduces the structural integrity of the solid rocket motor. Moisture in the air propagates into the propellant and reacts chemically with the polymer binder and reduces the number of structurally effective crosslinks resulting in reduced Young's modulus. This process is very slow but can be serious for rocket motors stored for a long-term period. Majority of aging studies on solid propellant uses experimental methods. Analytical model of aging process is inaccurate due to complex chemical processes involved and lack of property data needed for analysis.

4.1 Formulation of Model

The dominant aging mechanism of solid propellant is diffusion and chemical reaction of water vapor within the propellant binder, which is urethane-cross-linked polyester. The rate of aging process depends primarily on the rate of rupture of ester and urethane bonds. The rate of crosslink destruction is described by [10,11].

$$\frac{dXL_c}{dt} = -k_o XL_c - k_h C_{H_2O} XL_c$$

The first term is the results of chemical reaction of urethane with chemical species other than water in the propellant and the second term is the crosslink loss due to ester hydrolysis.

The moisture propagation into the propellant is convection-diffusion process described by [10, 11].

$$\frac{\partial C_{H_2O}}{\partial t} = \vec{\nabla}\cdot\left(D\cdot\vec{\nabla}C_{H_2O}\right) - \vec{\nabla}\cdot\left(C_{H_2O}\vec{V}\right) - k_h C_{H_2O} XL_c$$

By solving two equations simultaneously, we can determine the crosslink density of the propellant. In the present study, convection effects are neglected and only diffusion effects are considered. To handle sharp discontinuity at the interface of casing, liner and propellant, moisture concentration is replaced by the partial vapor pressure and the resulting equations are solved by finite volume method.

4.2 Simulation Results

Since the solid propellant grain of N-H sustainer motor is long in axial direction, it can be assumed that moisture propagation is two-dimensional on the plane perpendicular to the axis. This assumption simplifies the analysis by reducing 3-dimensional problem to 2-dimensional. Due to the symmetry, one-tenth segment of solid propellant is considered in the analysis as shown in Fig. 13.

Two-dimensional modeling revealed that the lumped capacitance method (kinetic model) could predict reasonably accurate aging process. This is due to the fact that air trapped inside the motor speeds the diffusion process because of its high molecular diffusivity compared with the diffusivity in the propellant. Fig. 14 shows kinetic model prediction of normalized crosslink density and normalized modulus in comparison with 2-D numerical result. Kinetic model slightly over predicts aging process. Thus it may be concluded that kinetic model can be used as a first approximation of aging process.

5. CONCLUSIONS AND RECOMMENDATIONS

This year efforts for the study of ignition transient for Nike-Hercules motor have been concluded. The study included several aspects of sub-tasks that are relevant to ignition transient phenomena. They are; (1) ignition transient modeling of aged Nike-Hercules motor using 1-D model to investigate the effects of aging process, (2) incorporation of radiation effects into existing 2-D Asymmetric model and (3) modeling of aging process in solid propellant.

All these goals were met at the conclusion of the current investigation. The effects of aging process could be qualitatively predicted by simulation of 1-D model. Simulation of N-H motor using newly designed igniter showed a marked improvement in term of stable flame spreading time. Additional comparison with test data is however required for the validity of numerical predictions. Incorporation of radiation effects into existing code was a very challenging problem since finite volume approximation must be made to radiative transfer equation. This step was successfully completed and the radiation model was tested by solving radiative heat transfer problem in axi-symmetric geometry with known solutions before incorporating it into 2-D code. The effects of radiation on N-H motor were however not significant except slightly decreased flame spreading time. This result is due to the assumptions of low extinction coefficient and zero scattering combustion gas in the motor. Aging study on the solid propellant showed that moisture migration through the motor casing decreases structural integrity of the propellant up to 50% in ten years. Also found in aging study is that a lumped capacitance method treating whole propellant as a thin block provides a good approximation. This is due to the presence of air in the bore of propellant. Air has a very large molecular binary diffusion coefficient and speeds up the diffusion of moisture from the inside surface of the propellant.

Ignition transients in solid rocket motor are complex physical processes that depend on many parameters, such as material properties of propellant, propellant grain shape, igniter design and others. Chemical and mechanical property changes that occur during long term storage make prediction of ignition transient even more difficult. A comprehensive study of ignition transient thus requires constant monitoring of propellant aging process and some live firing of candidate motors. Numerical modeling is a useful tool to augment experimental study if it is done carefully. Even though development of numerical algorithm for compressible reacting flow has been remarkable in recent years, numerical modeling has many limitations and should not be used as a stand-alone tool for prediction purpose.

To improve the prediction capability of ignition transient of solid rocket motors, continuing efforts should be directed to the refinement of numerical models; basic numerical formulation, burning rate laws, turbulent effects and more realistic radiation interactions. Aging model needs further improvements; additional chemical reactions other than moisture effects and convection effects due to pressure driven porous flow.

6. REFERENCES

1. Pardue, A. and Han, S., "Ignition Transient Analysis of Solid Rocket Motor Using One-Dimensional Two-Fluids Model," AIAA paper 92-3277, Joint Propulsion Conference, Nashville, TN 1992.
2. Han, S., "Ignition Transients in Space-Shuttle Solid Rocket Motor," Invited paper at Agency for Defense Development, Republic of korea, Aug. 1992.
3. Spalding, D. B., "Numerical Computation of Multi-Phase Flow," Von Karman Institute for Fluid Dynamics, Lecture Series, 198 1.
4. Chang, S. T., Han, S., and Chai, John, "Radiation Effects on I-D Ignition Transient Analysis of SRM, "AIAA Paper 96-3055, 32nd Joint Propulsion Conference, July, Buena Vista, FL, 1996.
5. Sutton, George P., Rocket Propulsion Elements. 5th Ed., John Wiley and Sons, 1986.
6. Rocket Motor Manual, CPIA/MI. Vol. 1, Chemical Propulsion Information Agency, Johns Hopkins University, 1994.
7. Han, S., and Chai, John, "Prediction of Ignition Transients in Rocket Motors," Interim report to Daeah Ind. Co., Korea, December 1997.
8. Bai, S. D., Han, S., and Pardue, A., "2-D Axisymmetric Analysis of SRM Ignition Transient," AIAA 93-2311, 29h Joint Propulsion Conference, June, 1993, Monterey, CA.
9. Chang, S. T., and Han, S., "Numerical Study of Ignition Transient in a Solid Rocket Motor," 20th International Pyrotechnics Seminar, July 1994, Colorado Spring, CO.
10. Bond, P. M., and Crowley, J. C., "Part 1: Finite Element Prediction of modulus Due to Age-Induced Mechanical Property Changes in Solid Rocket Motors," 1989 Joint JANNAF CMC/S&MB Subcommittee Meeting, Pasadena, CA.
11. Bond, P. M., and Fields, S. T., "Part II: Finite Element Prediction of Strain Due to Age-Induced Mechanical Property Changes in Solid Rocket Motors," 1989 Joint JANNAF CMC/S&MB Subcommittee Meeting, Pasadena, CA.

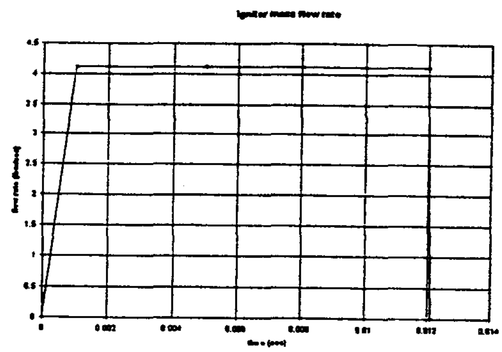


Fig.1 Igniter mass flow rate for N-H sustainer

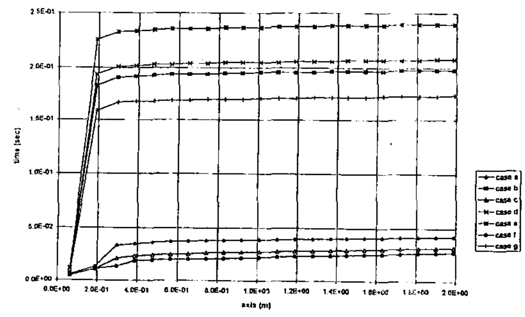


Fig. 2 Flame Spreading time for N-H Sustainer Motor With original Igniter

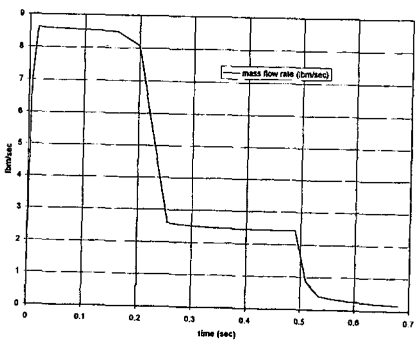


Fig. 3 New Igniter (NHIGN) Mass Flow Rate

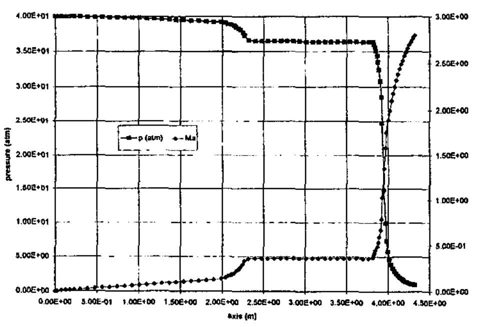


Fig. 4 Quasi-steady Pressure and Mach Number distribution in N-H Sustainer Motor with New Igniter (Base Case)

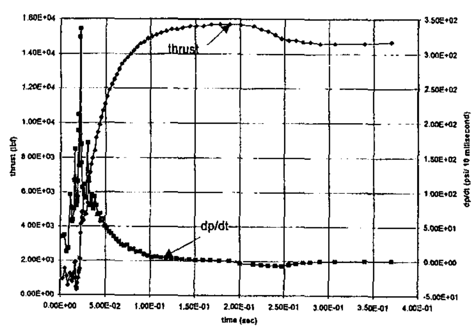


Fig. 5 Total Thrust and Head-end Pressure Gradient of N-H Sustainer Motor with New Igniter (Base Case)

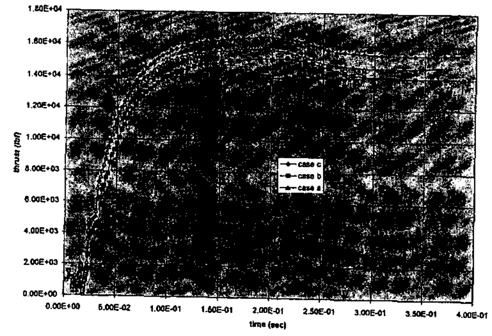


Fig. 6 Comparison of Total Thrust from N-H Sustainer Motor with New Igniter

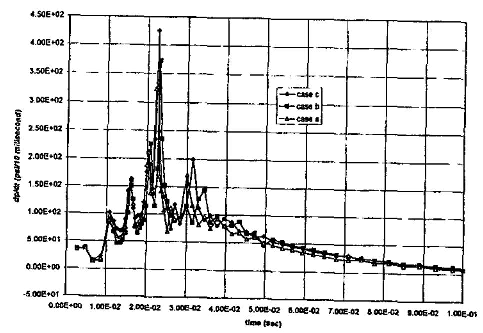


Fig. 7 Comparison of Head-end Pressure Gradient in N-H Sustainer Motor with New Igniter

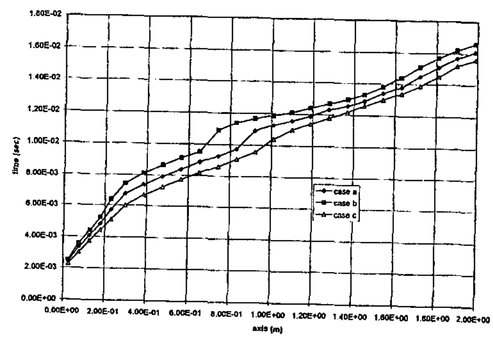


Fig. 8 Comparison of Flame Spreading Time in N-H Sustainer Motor with New Igniter

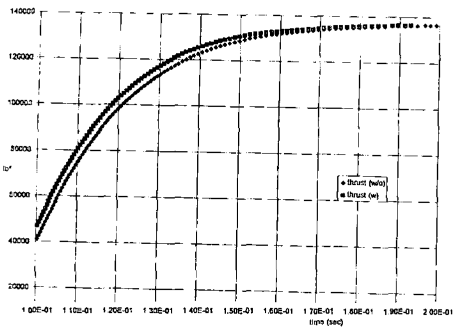


Fig. 9 Comparison of Total Thrust from N-H Sustainer Motor predicted by 2-D Axi-symmetric Model with and without Radiation Effects

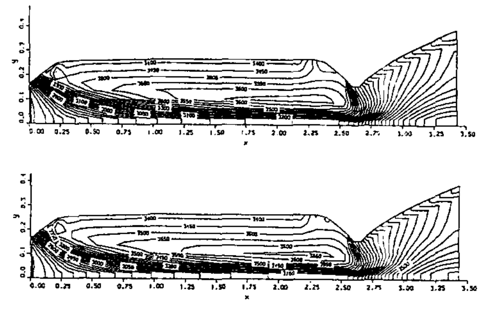


Fig. 12 Temperature distribution in Sustainer Motor Without (top) and With (bottom) Radiation

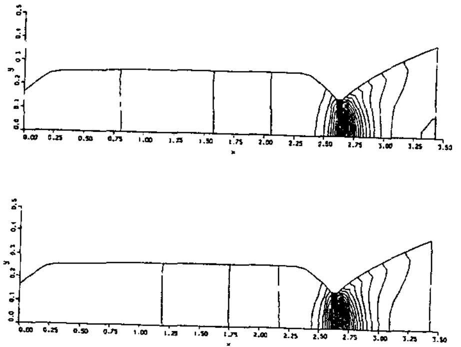


Fig. 10 Pressure distribution in N-H sustainer motor at t=0.1 sec without (top) and with (bottom) radiation effects

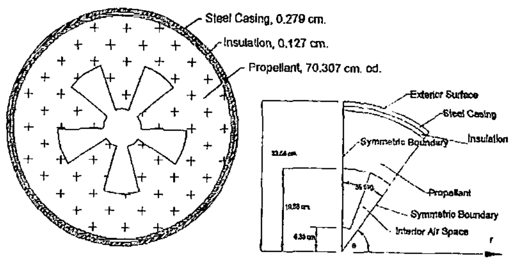


Fig. 13 Nike-Hercules Sustainer Motor Cross-section and a Pie Segment Computation Domain

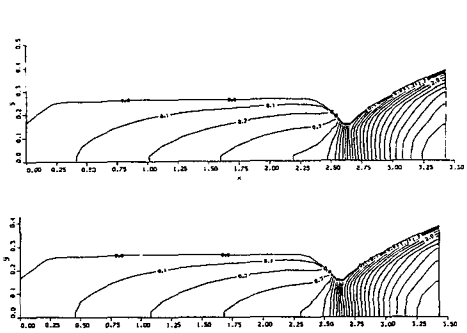


Fig. 11 Mach number distribution in Sustainer Motor Without (top) and With (bottom) Radiation

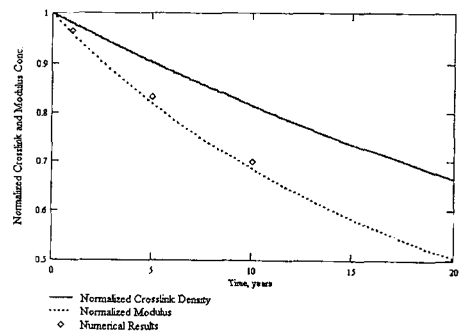


Fig. 14 Comparison of 2-D numerical prediction and kinetic model