MODELLING OF PLASMA AUGMENTED SOLID PROPELLANT COMBUSTION

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ABSTRACT

A modelling study is conducted to investigate the influence of plasma injection duration and location on the combustion of a granular solid propellant bed in a solid propellant electrothermal-chemical (SPETC) gun.. A number of models with varying degrees of complexities are used in the study and the results are compared. The parametric study shows the importance of injection duration, region and total electrical energy expended on gun performance.

INTRODUCTION

An important design parameter for guns is the maximum pressure allowed, which is dependent on the structural strength of the barrel. In general higher maximum pressures in the gun chamber (resulting in a larger area under the projectile-travel pressure curve) lead to higher performance, ie. kinetic energy of the projectile. Optimum performance of a given gun can be achieved by tailoring the pressure time curve to the structural strength of the gun barrel. This can be accomplished by controlling the burn rate of the propellant through grain design, chemistry and additional electrical energy input. Electrothermal-chemical (ETC) gun propulsion utilises an electrically generated plasma formed by a pulsed power system in conjunction with a chemical propellant to increase the performance and control of a gun system. The combustion process of solid propellants in an ETC system (SPETC) is initiated by the plasma, and the total energy is augmented by plasma injection into the gun chamber and/or in the barrel. The plasma is used to ignite the solid propellant bed and augment the chemical energy with electrical energy to achieve an enhanced performance. The plasma propellant combination provides control of the combustion process either directly through the burning rate of the propellant or by influencing the space-mean pressure and thereby the gas-generation-rate. A strong influence of the plasma on the burning rate of a solid propellant has been shown by an experimental investigation (Edwards et al, 1995). This is especially true for propellant beds with high loading densities, which are often not totally burnt-out at the end of the interior ballistic cycle when using conventional ignition stimuli. However, there is an optimal duration of injection of the plasma whereby the rate of electrical energy can be translated into projectile kinetic energy. In addition, the rate of electrical energy deposition can influence the optimal plasma duration.

The performance of SPETC guns, besides being dependent on the total electrical energy used, is also influenced by the time frame over which the electrical energy is deposited. There is a point in the interior ballistic cycle where additional electrical energy does not result in a significant projectile velocity increase. To explore the factors effecting performance a number of models of varying degrees of complexity have been developed to model interaction between plasma and solid propellant bed.

In this study we investigate the influence of plasma on the combustion process of a solid propellant bed. Zero-, one and two dimensional codes are utilised in the study of expansion of the plasma and the translation of electrical energy into projectile kinetic energy.

MODEL DESCRIPTIONS

0-D Model

The lumped parameter model IBHVG2.ETC (Ernhart et al, 1994) includes the major physical processes, treating however the regions of the gun uniformly in regards to the physical properties. A Lagrange pressure gradient between the breech and the base of the projectile is assumed; and communication is instantaneous. The model assumes that the plasma energy is a source term in the overall energy equation. the plasma properties based on experimental data or design parameters for the plasma injector are used as input parameters in each time step. The nature of the model implies a direct relationship between the chemical and electrical energy expended and the gun performance. The position (being a (0-D model) and duration of plasma injection (as long as the projectile is still in the barrel) has no influence on the performance predictions.

1-D Model

One-dimensional two-phase flow models allow a more accurate description of the interior ballistic process. The XNOVAKTC (XKTC) code has been developed by Paul Gough Associates (1983). For a detailed basic description of the code the authors refer to reference (Gough, P.S, 1979). The code is based on the one-dimensional transient heterogeneous two-phase flow equations. The balance equations for energy, mass and momentum for the two phases are solved numerically using an explicit finite difference (McCormack predictor/corrector) scheme. The covolume equation of state for the gas phase supports the balance equations. A control volume approach computes average flow properties in a cell large in comparison to the size of propellant grains.

The complex processes between the boundary layers of the two phases are not modelled from first principles. Assumptions have been made that empirical correlations for interphase drag, heat transfer and combustion rate adequately describe the physical processes. The propellant bed is contained between the gun breech face, gun chamber walls and the base of the projectile which are the external boundaries.

The plasma source represents a boundary condition and is incorporated as a source of mass, momentum and energy in the gas-phase balance equations. The plasma is described using a plasma mass and energy flux which is added to the gas phase over a mixing length. one or multiple plasma sources can be modelled. the plasma jets are represented by a number of fixed regions and overlapping of the regions can be examined. the plasma is specified by experimental data or design parameters including the plasma energy, plasma mass flux over time, and mixing length.

The decomposition of the propellant is modelled using a burning rate law, where the burn-rate is dependent on pressure.

2-D Model

It has been shown in previous studies (Wren et al, 1995), that the spatial distribution of the plasma plays an important role in the interior ballistic cycle of ETC guns, particularly when high electrical energy densities are involved. As already pointed out, the plasma influences the combustion behaviour of the propellant. We assume, however, that the effect is confined to the area where the plasma penetrates the propellant bed and interacts directly with the propellant. To be able to estimate which propellant grains are in contact with the plasma, the code would have to keep track of the axial and radial position of single propellant grains. Furthermore, a 1-D interior ballistic code is not able to handle any radial penetration of the plasma and in addition, only bulk properties of the propellant, eg average porosity, in each computational cell, can be considered. This makes it important to apply a code which is able to track the position of single propellant grains and to compute the radial penetration of the plasma.

The 2-D gun propulsion version of the CRAFT code (Hosangadi et al, 1994) developed by Combustion Research and Flow Technology Inc., is based on first principles . The code solves reacting, multi-phase, multi-component fluid flow equations and allows the computation of the 2-D solid propellant interior ballistics flow fields. The two-phase flow is described as a mixture of continuum fluid (which can be liquid, gas or a combination of liquid and gas) and an aggregate of incompressible particles. The gas phase equations for dense two-phase flows are similar to those used in the 1-D XKTC (Gough, 1983) code. A Lagrangian formulation describes the motion of the propellant grains where each grain is tracked independently in terms of dimension, motion and gas generation rate. Similar empirical relations used in the 1-D code are utilised for drag and heat transfer to model the processes occurring between the solid propellant and the gas surrounding it. Non-equilibrium between the two phases as well as phase-change for the particles as they heat up or cool down are considered. Combustion is modelled with the dependent burning-rate law. The numerics used are an implicit higher order upwind (Roe/TVD) formulation with fully implicit source terms and boundary conditions.

PARAMETRIC STUDY

A parametric study was conducted to consider a number of parameters including injection duration, injection region, number of injection ports and total amount of electrical energy consumed. For the parametric study the 0-D and 1-D codes are utilised.

For the following simulations a square electrical pulse shape with a constant electrical power level was assumed. The parameter varied was the duration of the pulse; therefor the total electrical energy input was dependent on the injection time. The simulations were conducted for four different power levels (125, 250, 500 and 750 MW power). The propellant mass and with it the chemical energy input was constant for all simulations.

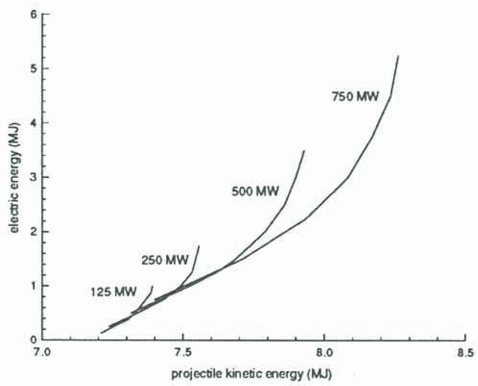

Figure 1 0-D model predictions: influence of electrical energy input on projectile kinetic energy

Figure 1 shows the results for the 0-D simulations. As one can see the projectile kinetic energy increases with increase in electrical energy. This is consistent with the assumption of the lumped parameter model, which infers an instantaneous communication between the breech and the base of the projectile via a pressure gradient relationship. Therefore, only the total plasma energy injected into the chamber is important. The relationship between amount of plasma energy injected and increase in projectile kinetic energy is not linear. The reasons for that are increasing heat losses and higher combustion gas temperatures and pressures at gun exit with increasing electrical energy input.

Figure 2 shows the results for the 1-D model. the predictions show an initially strong increase in projectile kinetic energy with increasing electrical energy levels. However, after reaching a particular power input level the projectile kinetic energy stays constant. Additional plasma injection after this point has only an effect on gas temperatures in the area near the breech. .

This is confirmed by Figure 3, which depicts the temperature contour in the gun from breech to projectile base in the interior ballistic cycle with an injection duration of 4 ms. As one can see, the gas temperatures stay above 2000 K only up to approximately 4 ms. This implies after a certain time the plasma heated gases do not reach the projectile and consequently do not influence the performance of the gun.

In Figure 4 an electrical efficiency versus electrical energy input has been depicted. The electrical efficiency is computed using the following expression:

$$\frac{KE_{tot} - KE_0}{EE} = e_{eff}$$

where KE_{tot} is the total kinetic energy of the projectile, KE_0 is the projectile kinetic energy derived from simulation without electrical energy (only chemical energy of propellant), EE the electrical energy expended and e_{eff} is the electrical energy efficiency factor. As can be seen there is a point for each power level where losses are minimised and the electrical energy input is used most efficiently.

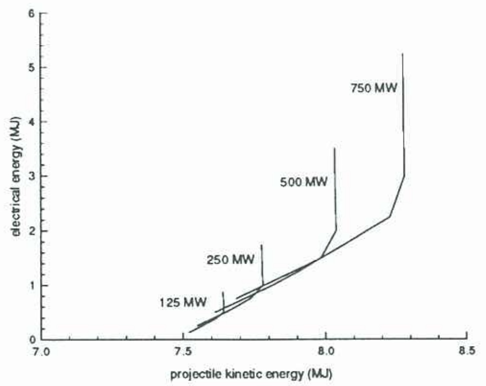

Figure 2 1-D model predictions: influence of electrical energy input on projectile kinetic energy

The previous simulation suggest, that by injecting the electrical energy at different positions along the gun barrel, the high temperature regime of the gases at the projectile base could be extended. Table 1 shows an example where a number of injection points were utilised along the barrel. The example is by no means an optimisation; however, it gives an indication of the performance improvements feasible when a number of plasma jets along the gun barrel are utilised. Case 1 is the baseline case where the total electrical energy is injected at the breech end. In case 2 four plasma ports are utilised along the barrel. An improvement of approximately 11 % in projectile kinetic energy was reached, with the same chemical and electrical energy expended.

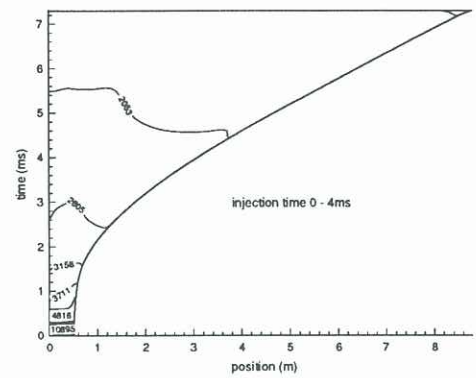

Figure 3 1-D model predictions: temperature contours for 4 ms plasma injection duration

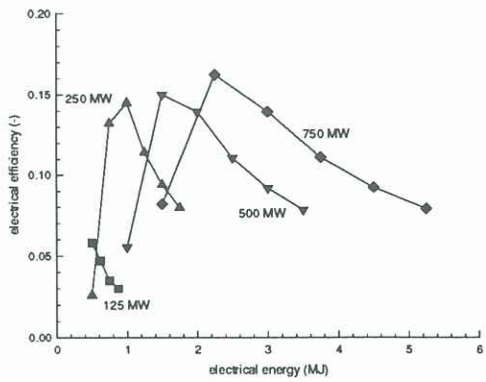

Figure 4 1-D model predictions: influence of power on electrical efficiency

Table 1. Influence of Injection Region on Projectile Kinetic Energy

case	plasma position	injection duration	projectile kinetic energy	electrical energy
	(m from breech)	(ms)	(MJ)	(MJ)
1	0.00	0 - 7	8.23	5.00
2	0.00	0 - 3.0		0.625
	0.40	3.0 - 4.5		0.625
	1.40	4.5 - 5.0		1.250
	2.80	5.0 - 5.5		2.500
total case 2			9.11	5.000

SPATIAL EFFECTS OF PLASMA

To investigate the spatial effects of the plasma, the 2-D CRAFT code is utilised (Hosangadi et al 1994).

Figure 5 shows an example of a 2-D simulation, the temperature profiles for various time steps are shown. The plasma injection duration for the case modelled was 1.77 ms. The y axis depicts the radial position and the x-axis the axial position (centreline). The temperature is plotted in a logarithmic dimensionless scale, normalised with the plasma temperature (15000 K) in order to provide a better display of the results. The plasma is injected from the breech end into an ullage tube. the propellant is loaded around the ullage tube and the initial pressure ratio between the volume taken up by the propellant bed and the ullage tube is assumed to be 0.1. At time zero the plasma injection begins from the breech. The plasma expands rapidly, radially, cooling and creating a region of turbulence at the breech end as can be seen on the temperature contour at time 0.0822 ms. The hot gas impacts the projectile base where it stagnates and is reflected. At time 0.4553 ms a hot plasma core can be observed, surrounded by a much cooler propellant bed. The temperature profile indicates that heat transfer and ignition of the propellant bed has occurred, and a strong radial temperature gradient is indicated. At that time the projectile has started to move (initial projectile position 0.195 m). The plasma is reflected from the projectile base and a wavy structure can be seen in the temperature profiles. The structure is thought to be due to a combination of a rarefaction wave and vigorous plasma injection. It can be concluded from the next time step depicted in the graph (1.0242 ms), that the plasma needs a finite time to propagate through the gas and combustion products and in the later stages of the interior ballistic cycle the plasma heated combustion products do not reach the projectile any more. This confirms the prediction of the 1-D model.

A strong temperature gradient in radial direction for all time steps can also be observed. The figure suggests, that the plasma products do not reach the chamber walls and have only a local influence. this has some advantage, since the temperature at the chamber walls are not high enough to cause erosion of the gun tube. However the cool regions at the chamber walls suggest a lower local burning rate of the propellant, which could result in less efficient combustion and lower performance.

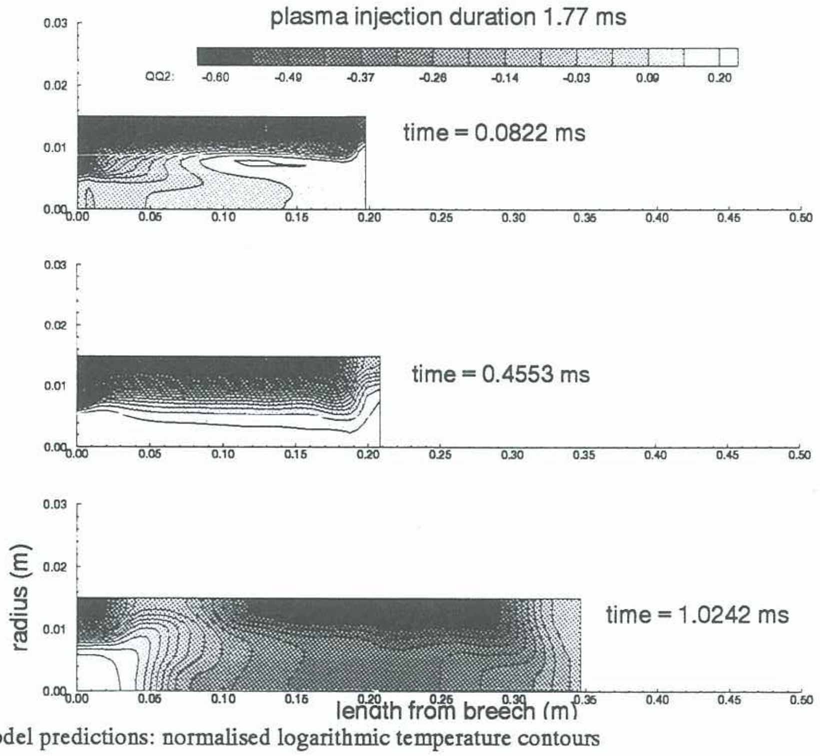

Figure 5 2-D model predictions: normalised logarithmic temperature contours

CONCLUSIONS

A number of plasma related parameters were considered in the simulations. The results showed, that for the 0-D model only the total electrical energy expended is important. The 1-D parametric study revealed, there is a cut-off point in the interior ballistic cycle where additional electrical energy input does not result in a projectile kinetic energy increase. The 2-D simulations displays strong spatial effects in the temperature profiles.

REFERENCES

Edwards, C.M., Bourham, M.A., and Gilligan, G., 1995, "Experimental Studies of the Plasma Propellant Interface for Electrothermal-Chemical Launchers", 7th Electromagnetic Launch Symposium, to be published IEE Transactions on Magnetics.

Ernhart, J.N., Winsor, N. and Wren, G.P., 1994, "Electrothermal-Chemical (ETC) Extensions to IBHVG2 with a new User's Tutorial", US Army Research Laboratory Technical Report ARL-TR-348

Gough, P.S., 1983, "XNOVA - An Express Version of the NOVA Code", Naval Ordnance Station Indian Head, Contractors Report PGA-TR-83-5

Gough, P.S., "Interior Ballistics of Guns", (H.Krier, M. Summerfield Eds), Progress in Astronautics and Aeronautics, AIAA, New York, 1979, Vol. 66, pp.176-196

Wren, G.P., Oberle, W.F., Winsor, K.N., Hosangadi, A., "Spatial Effects of an Electrically Generated Plasma on the Interior Ballistics of Electrothermal-Chemical (ETC) Guns", IEE Transactions on Magnetics, 1995, Vol.31, No.1, pp457-462

Hosangadi, A., Sinha, N. and Dash, S.M., "Multi-Dimensional Simulation of ETC Gun Flowfields", Contractor report, SAIC/FW TR-121, Febr. 1994