Defense Technical Information Center Compilation Part Notice

ADP023641

TITLE: Modeling of Plasma Induced Ignition and Combustion

DISTRIBUTION: Approved for public release, distribution unlimited

This paper is part of the following report:

TITLE: Army Research Office and Air Force Office of Scientific Research Contractors' Meeting in Chemical Propulsion Held in Arlington, Virginia on June 12-14, 2006

To order the complete compilation report, use: ADA474195

The following component part numbers comprise the compilation report:
ADP023616 thru ADP023650

UNCLASSIFIED

Modeling of Plasma Induced Ignition and Combustion

Michael Keidar, Iain D. Boyd and Andy Porwitzky
University of Michigan

Abstract-Electrothermal-chemical (ETC) ignition systems have been demonstrated in gun systems to provide desirable characteristics including reproducible shorter ignition delays. We present a combined theoretical and experimental study of the capillary discharge with an aim to develop a capillary plasma source with efficient energy conversion. In addition, a detailed understanding of the dynamics of the plasma-propellant interaction is considered one of the key elements to the future success of practical ETC gun implementation. We address this issue by developing a model of the propellant ablation under plasma effect based on the kinetic theory of ablation. The major emphasis in the present capillary discharge model is the ablation phenomenon. A kinetic approach is used to determine the parameters at the interface between the kinetic Knudsen layer and the hydrodynamic layer. In parallel, a parametric experimental study of the capillary ablation process is conducted at Army Research Laboratory. Both experimental measurements and simulations indicate that the ablated mass increases with the peak discharge current and that a smaller diameter capillary yields a larger ablated mass. It is found that model predictions agree well with experimental measurements. The ablation model is coupled with a model of the plasma generation in the capillary discharge that allows calculation of the effective heat flux from the plasma. Calculations are performed for specific experimental conditions in which ablated mass of a double-base and a nitramine composite propellant are studied. One representative solution reproduces the experimentally determined ablated mass for the double-base propellant of 5.3 mg via an effective heat flux on the order of 4×10^8 J/m^{2}s. The effective heat flux that corresponds to the experimentally measured ablated mass is determined for different propellants. Differences in the calculated effective heat flux between different propellants indicate that although heat convection from the plasma is the dominant source of energy, plasma radiation and the optical properties of the propellants themselves can not be ignored.

1. Model of a capillary sustained plasma

We present a capillary model for an ETC that includes self-consistent consideration of the ablation phenomena. In this section, the model is described for the plasma generation processes (ablation, heating, radiation, ionization etc.) and plasma acceleration along a capillary of a pulsed electrical discharge. Figure 1 shows some characteristic regions in the interface between the discharge plasma and the dielectric wall such as an electrical sheath near the dielectric, the Knudsen and hydrodynamic layers, and a quasi-neutral plasma. Different kinetic and hydrodynamic phenomena determine the main features of the plasma flow including Joule heating, radiative and convective heat transfer to the dielectric, and electrothermal acceleration of the plasma up to the sound speed at the cavity exit. The central region is the quasi-neutral plasma that occupies almost the entire capillary since typically the transition region scale length is much smaller than the capillary radius. The plasma region is separated from the dielectric surface by the vapor layers (Knudsen layer and hydrodynamic layer). Finally, the plasma-wall transition region includes the electrostatic sheath attached to the wall. The plasma is heated due to electric current flowing through the capillary. The energy transfer from the plasma column to the capillary wall consists of the heat transfer by particle fluxes and radiation heat transfer. Energy is absorbed by the capillary walls and dissipated by thermal conductivity and material evaporation.

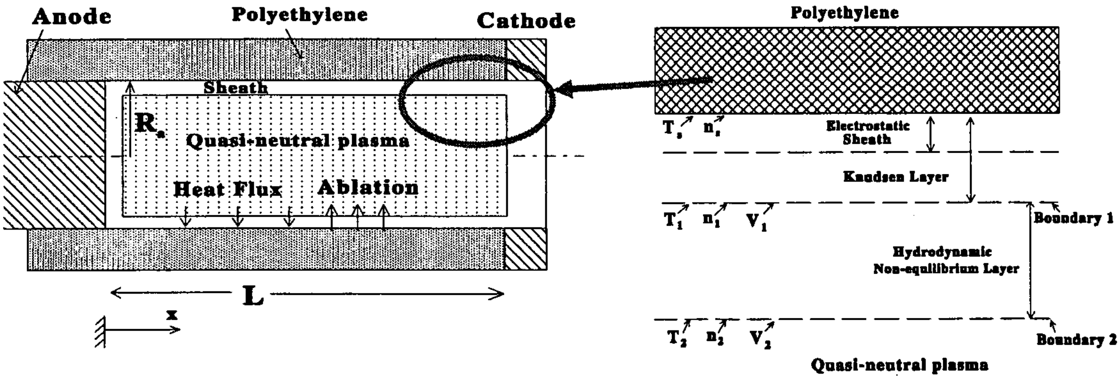

Figure 1. Schematic of the problem geometry (not to scale) and multi-layer structure near the ablated surface.

Ablated flux builds up a vapor layer in the vicinity of the wall. Under the considered conditions the mass, momentum and energy conservation equations have the following forms:

$$A\left(\frac{\partial \rho}{\partial t}+\frac{\partial \rho V}{\partial x}\right)=2\pi R_a \Gamma(t,x) \quad (1)$$

$$\rho\left(\frac{\partial V}{\partial t}+V\frac{\partial V}{\partial x}\right)=-\frac{\partial P}{\partial x} \quad (2)$$

$$\rho\left(\frac{\partial \varepsilon}{\partial t}+V\frac{\partial \varepsilon}{\partial x}\right)=-P\frac{\partial V}{\partial x}+Q_j-Q_r-Q_F \quad (3)$$

where $\varepsilon=\frac{3}{2}\frac{T_p}{m}+\frac{V^2}{2}$. The radiation energy flux Q_r includes the radiation for a continuum spectrum. The particle convection flux Q_F includes energy associated with electron and ion fluxes to the dielectric wall that lead to plasma cooling. More details about the capillary model can be found elsewhere [3,4].The capillary wall ablation is modeled in the framework of the previously developed kinetic model. [5] Two different layers between the ablated surface and the plasma bulk are considered as shown in Fig. 1: (i) a kinetic non-equilibrium layer adjacent to the surface with a thickness of about one mean free path; and (ii) a collision-dominated layer with thermal and ionization non-equilibrium. The plasma-wall transition layer includes also an electrical sheath described below. Based on the developed, the model plasma parameter distribution in the capillary was calculated.

In this study we consider a specific capillary plasma source for an ETC developed at the Army Research Laboratory and described recently elsewhere [1,4]. Capillary geometry determines the ablation process in the capillary by affecting the mass and energy balance. The dependence of the ablated mass on the peak discharge current is shown in Fig. 2. The ablated mass has a linear dependence on the discharge peak current. For comparison, experimental data are also shown in Fig. 2. It can be seen that both simulations and experiment suggest that the ablated mass increases as the capillary inner diameter decreases. This effect is explained by increased current density in the capillary, which affects the ablation rate through Joule heating. Reasonable agreement is obtained although the predicted ablated mass is lower than that measured in the experiments. It should be pointed out that the above calculations were performed assuming that returned atoms and ions do not form film at the polyethylene surface. On the other hand it can be considered that only carbon atom and carbon ion deposition takes place, as the hydrogen atoms and ions will be re-evaporated [8]. The last assumption is supported by previous studies of dielectric (Teflon) ablation into C-F plasmas which indicated that a dielectric can be significantly carbonized (charred) dependent on operational conditions.[8] In this study we also investigate parametrically effects of condensation at the dielectric surface. We introduce a new parameter, ν, which is the fraction of the backflux that condenses at the surface. In the case of $\nu=1$, all particles returning to the surface will condense, while small parameter ν means that only a fraction of the backflux forms the film. Dependence of the ablated mass on this parameter is shown in Fig.3. One can see that the best agreement with experimental data is achieved if $\nu=0.6$-0.7.

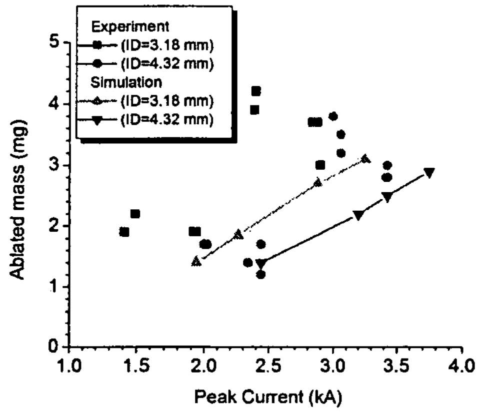

Figure 2. Dependence of the ablated mass (polyethylene) on the peak discharge current. Comparison of experiment and simulations.

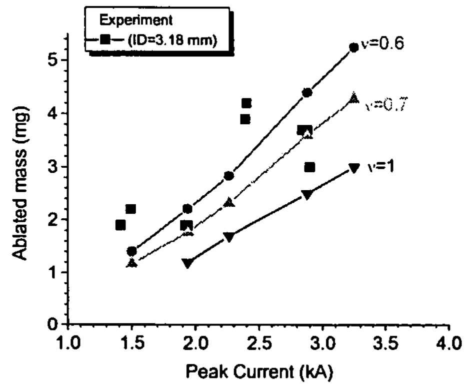

Figure 3. Dependence of the ablated mass (polyethylene) on the peak discharge current with deposition fraction as a parameter. Comparison of experiment and simulations.

2. Modeling of the plasma-propellant interactions

Plasma-propellant interactions are modeled based on the kinetic theory of ablation model which was adapted from previous work by Keidar *et al* [5]. To model the propellants, vapor pressure and enthalpies of sublimation are calculated via an averaging technique based on their percent composition of constituent compounds obtained from Miller [6], as no experimental data is available. The ablation model is coupled with a 1-D thermal model to predict the surface heat flux, q, incident on the propellant. More details can be found in Ref. 7.

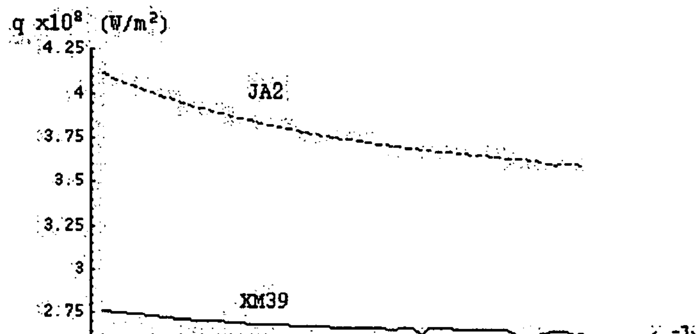

Fig. 6. Effective plasma heat flux to each propellant predicted by model, where ΔM is the experimental value.

The effective heat flux can be modeled as $q = q_{conv} + q_{rad}$, the sum of the convective (particle flux) and radiation heat fluxes, respectively. The radiation flux is thus the difference of q and q_{conv}. Heat flux q and plasma density n_o are used as parameters in the thermal model. Once the surface temperature profile during the pulse is determined it is combined with the estimate for surface temperature after the pulse and numerically integrated to yield a total ablated mass for some q, n_o pair. It is assumed that for both propellant samples, the capillary generates a plasma with identical properties. Thus any differences in the incident heat fluxes are due to differences in the propellants themselves. The model predicts that JA2 will consistently have a higher effective heat flux than XM39 (Fig. 4), and that XM39 will have a higher surface temperature. As plasma density increases, heat flux (or surface temperature) will decrease, as evident in Fig. 4.

A comparison of the optical properties of the two propellants is made. Nitramine composite propellants are opaque to most wavelengths, and studies indicate that they do not allow radiation to penetrate and effect change in-depth. It has been demonstrated that JA2 allows radiation to penetrate in-depth, with physical and chemical changes occur up to approximately 1 mm into the propellant. In addition, it has been determined in experiments that XM39's reflectivity may be as high as 50% [7]. This evidence suggests that the difference between the heat flux to JA2 and XM39 is due to the optical properties of each propellant, specifically to penetrating radiation from the plasma. As noted earlier, the radiative heat flux for JA2 is expected to be much higher than for XM39, although XM39 should still have a small radiative flux due to surface heating. Thus the difference between the heat flux to each propellant, Δq, can be roughly interpreted as the difference in penetrating radiation flux between the propellants. It should be noted that Δq represents only a small fraction of the radiative heat available in a black body plasma at Te=1.5 eV. This can be partially explained by indications that vaporized propellant can act as a plasma radiation shield, helping to block some of the radiation flux [1]. Continuing this line of reasoning, $\Delta q/q_{JA2}$ can be approximated as the percent of JA2's heat flux attributable to penetrating radiation (Fig. 5), which drops from 33% at low density to 28% at high density. This indicates that the percentage of heat flux due to radiation is responsible for between a quarter and a third of the total effective heat flux received by the propellant.

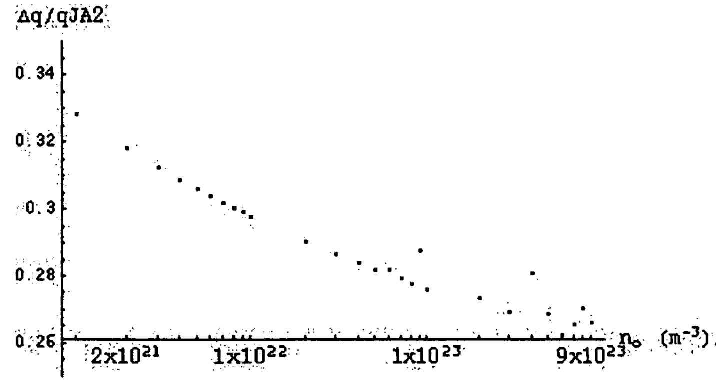

Fig. 5. $\Delta q/q_{JA2}$, the dependence of the fraction of radiation flux on the plasma density, in the vicinity of the propellant.

Acknowledgment

The authors gratefully acknowledge the financial support by the Army Research Office, Grant No. W911NF-04-1-0251 (Dr. Kevin McNesby, technical monitor). The authors also thank Dr. Dick Beyer, Dr. Michael Nusca, Dr. Anthony Williams, and Dr. Rose Pesce-Rodriguez from the Army Research Laboratory for very useful discussions and suggestions.

References

[1] R.A. Beyer and R. A. Resce-Rodrigues, "Experiments to define plasma-propellant interactions", IEEE Trans. Magnetics, vol. 39, 2003, p. 207

[2] J. Li, T.A. Litzinger and S.T. Thynell, "Interaction of capillary plasma with double-base and composite propellants", J. Prop. Power, vol. 20, 2004, p. 675

[3] M. Keidar and I.D. Boyd, Ablation study in the capillary discharge of an electrothermal gun, *Journal of Applied Physics* , vol. 99, 053301, 2006.

[4] M. Keidar, I.D. Boyd, A.W. Williams and R.A. Beyer, Ablation phenomena in a capillary sustained plasma, 13th Electromagnetic launch Symposium, Berlin, Germany, June 2006, Paper 161

[5] M. Keidar, I. D. Boyd and I. I. Beilis, "On the model of Teflon ablation in an ablation-controlled discharge," *J. Phys. D: Appl. Phys.* vol. 34, pp. 1675-1677, 2001.

[6] M. S. Miller, "Thermophysical Properties of Six Solid Gun Propellants," *ARL-TR-1322*.

[7] A. J. Porwitzky, M. Keidar and I.D. Boyd, Modeling of the plasma-propellant interaction, 13th Electromagnetic launch Symposium, Berlin, Germany, June 2006, Paper 162

[8] M. Keidar, I.D. Boyd, E. Antonsen, F. Gulchinski, G.G. Spanjers, "Propellant charring in pulsed plasma thrusters", J. Prop. Power, vol. 20, pp. 978-984, Nov. 2004.