Computational Analysis and Design of the Electrothermal Energetic Plasma Source Concept

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ABSTRACT

Electrothermal (ET) Plasma Technology has been used for many decades in a wide variety of scientific and industrial applications. Due to its numerous applications and configurations, ET plasma sources can be used in everything from small scale space propulsion thrusters to large scale material deposition systems for use in a manufacturing setting. The sheer number of different types of ET sources means that there is always additional scientific research and characterization studies that can be done to either explore new concepts or improve existing designs.

The focus of this work is to explore a novel electrothermal energetic plasma source (ETEPS) that uses energetic gas as the working fluid in order to harness the combustion and ionization energy of the subsequently formed energetic plasma. The goal of the work is to use computer code and engineering methods in order to successfully characterize the capabilities of the ETEPS concept and to then design a prototype which will be used for further study.

This thesis details the background of ET plasma physics, the ETEPS concept physics, and the computational and design work done in order to demonstrate the feasibility of using the ETEPS source in two roles: space thrusters and electrothermal plasma guns.

Acknowledgments

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Chapter 1
Introduction

1.1 Project Background and Objectives

Electrothermal plasma sources are well known for their adaptability to suit a large variety of tasks. Often times, a single type of ET source can be used in multiple applications. In order to fully understand the capabilities and limitations of such devices, characterization and design studies are of the utmost importance. Experimental work is often costly and time consuming; as such, computational modeling is instrumental in allowing the scientific community insight into the capabilities of a particular source design. This allows for focused selection of a new source concept based on the needs of a particular project. The primary focus of this project is to characterize the capabilities of a new type of electrothermal plasma source that currently has not been studied in depth: the electrothermal energetic plasma source concept (ETEPS) first introduced by AL Winfrey et al. [1] in 2014.

The ETEPS concept has two distinct modes of operation, ablative and non-ablative. The ablative ETEPS concept operates in a similar manor to ablative capillary discharge sources with the exception that the ablative liner is an energetic material of some sort. Thus, the electrical energy of the plasma is combined with the combustive energy of the dissociation of the energetic liner. The non-ablative ETEP source operates by injecting an energetic gas or liquid propellant into a confined non-ablative capillary. Upon injection of the propellant, a current arc discharge occurs between the anode and cathode, forming a plasma from the dissociation of the propellant material. This dissociation releases the chemical energy of the energetic propellant, thereby allowing mixing of the chemical energy with the electrical energy present in the plasma. This thesis only deals with the non-ablative ETEPS concept. The work done for this thesis involves analyzing the requirements for space propulsion thrusters and ET projectile launch systems and characterizing the ETEPS plasma ejection within this context. Due to the large range of requirements for these two diverse applications, this work will allow for a greater understanding of the capabilities of the ETEPS design and how it can be applied to a variety of applications.

The main objectives of this thesis are:

- To determine the key physical parameters governing space propulsion and electrothermal launch applications.
- Computationally characterize ETEPS with respect to the aforementioned physical parameters.
- Design an ETEP source based on the computational results.

1.2 Electrothermal Source Background

To better understand the novel nature of the ETEPS concept and provide context within the wider world of ET sources, a perfunctory review of the current scientific literature on ET technology follows. The focus of scientific study with regards to electrothermal sources has revolved around three main applications: fusion reactor refueling, space propulsion, and electrothermal-chemical (ETC) weapon systems. For the sake of this paper, the latter two topics of space propulsion and ETC systems will be addressed.

Electric thruster systems have been used on satellites for both station keeping and as primary propulsion sources [2, 3, 4, 5]. Among the most common electric thruster systems are electrothermal plasma thrusters. ET thrusters are commonly divided into two main categories: resistojets and arcjets, both of which use electrical energy to heat a gaseous or liquid propellant in order to provide additional energy to the propellant exit stream [6]. As shown in Figures 1.1 and 1.2, resistojets use a filament to heat a propellant gas to a higher temperature while arcjets pass the propellant through a current arc. Of the two systems, only the arcjet produces a plasma.

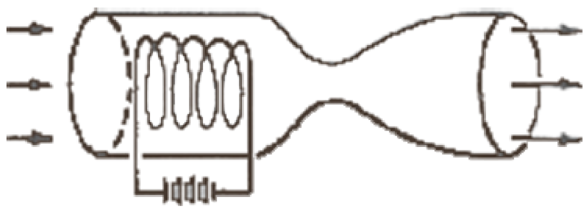

Figure 1.1: A simplified diagram of a resistojet propulsion system.

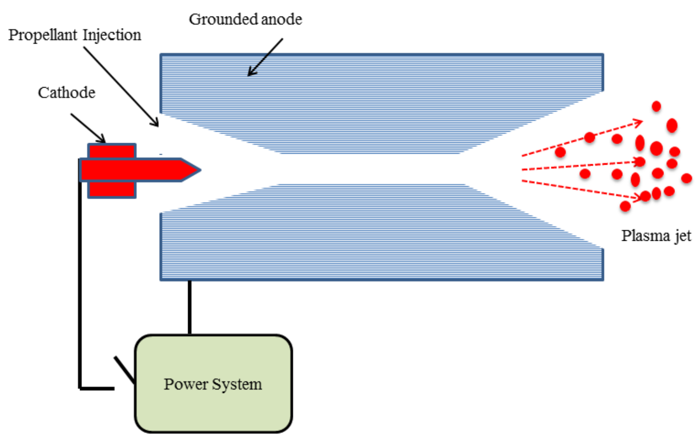

Figure 1.2: A simplified diagram of an arcjet propulsion system.

The ETEPS concept is similar to an arcjet; however, the mode and parameters of operation differ significantly. For instance, arcjets typically have a current arc on the order of 10A [6, 7] whereas the ETEP source generally operates on the order of 10kA in order to achieve ionization of combustion products. Arcjets generally operate in a continuous mode of operation, whereas ETEPS operates in a pulsed mode with discharge lengths of approximately 150μs or less. Both ETEPS and arcjets use an arc discharge produced by a voltage difference between the anode and the cathode as the primary means of energy conversion. The applied voltage for Arcjet thrusters power supply is general on the order of 10 - 100V, whereas the ETEP source generally operates in the 1 - 10kV range.

An additional use for electrothermal sources is as igniters for electrothermal chemical weapon systems [8, 9]. The purpose of ETC technology is to use an ET source as an igniter for a bulk packed propellant. The propellant is what provides the majority of the kinetic energy required to propel the projectile forward; however, the ET source can control the burn characteristics of the bulk propellant. Conventional gun technology currently uses a primer, which is a force activated explosive, as an ignition source for the main propellant. Due to the variable nature of the primer ignition, the burn characteristics of the main propellant vary for each projectile launch [10]. Environmental variables such as temperature and humidity can also alter the burn characteristics of the propellant. All of these variables can add up over extended ranges such as those required for large caliber naval guns or land based artillery. Using an ET ignition source allows for a larger degree of control over the burn characteristics of the propellant, thereby increasing the accuracy and muzzle energy of the system. An example of an ETC gun can be seen in the figure below.

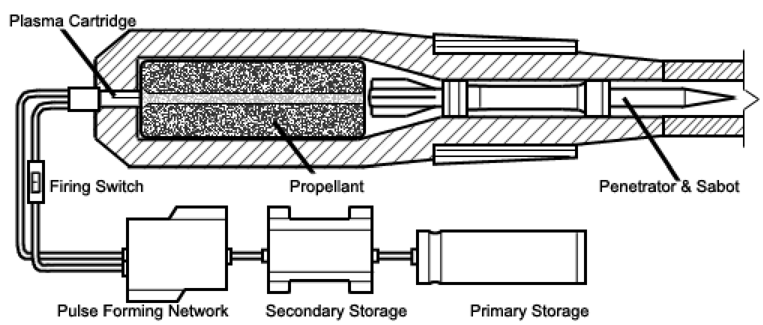

Figure 1.3: Electrothermal Chemical gun diagram [11]. Catalan at English Wikipedia. Electrothermal chemical gun. http://commons.wikimedia.org/wiki/File:ETC.png, 2015. [Online; accessed April 1, 2015]. Used under fair use, 2015

The ETEPS concept aims to combine the propellant and the ignition source to allow for greater control over launch ballistics. Both the ablative and non-ablative ETEP source can be used in place of an ET igniter in order to enhance control of the ignition and burn characteristics. For instance, the burn time of the propellant can be changed by increasing or decreasing the bulk velocity of the ejected plasma. Increasing or decreasing plasma temperature can either improve or decrease the propellant burn efficiency. In addition to replacing the igniter, the sources can also be used as a standalone launch system, where the ETEP source provides all of the pressure and bulk propellant velocity needed to launch a small caliber projectile. A diagram of an ablative ETEP source is shown below.

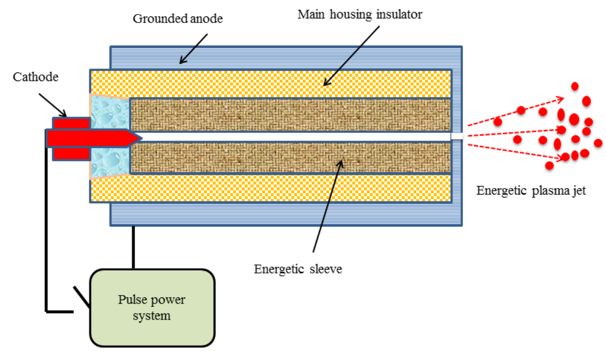

Figure 1.4: Ablative ETEP source diagram.

The work that has been done in electrothermal plasma analysis is incredibly extensive and cannot be fully discussed in this section; however, it is important to understand where the ETEPS characterization work falls within this broad field of study. The ETEP source is a novel electrothermal plasma generation source that has the potential to either replace or supplement many of the current electrothermal plasma sources currently being used. It is the broad range of plasma characteristics that ETEPS can generate that are being investigated within this thesis.

Chapter 2
Plasma Physics

2.1 Ionization

In order to understand the physics behind the simulation code used to model and characterize the ETEPS concept, it is important to get a firm grasp over the basics of plasma physics. Plasma, often said to be the fourth state of matter, can be described as a soup of ions and electrons. It is a quasi-neutral mass of unbound positive and negative particles [12]. A plasma can be formed out of a solid, liquid, or a gas. As long as the temperature is hot enough, ionization occurs, separating electrons from the atoms of the material being ionized. These separated electrons collide into other atoms, causing further ionization. Examples of plasmas in every day life include but are not limited to neon signs, fluorescent light bulbs, auroras, and lightning. To maintain a plasma, the plasma temperature must be kept high enough to prevent a substantial amount of recombination to occur in the ionized gas. The process of collisional ionization and recombination can be seen in Figure 2.1 below.

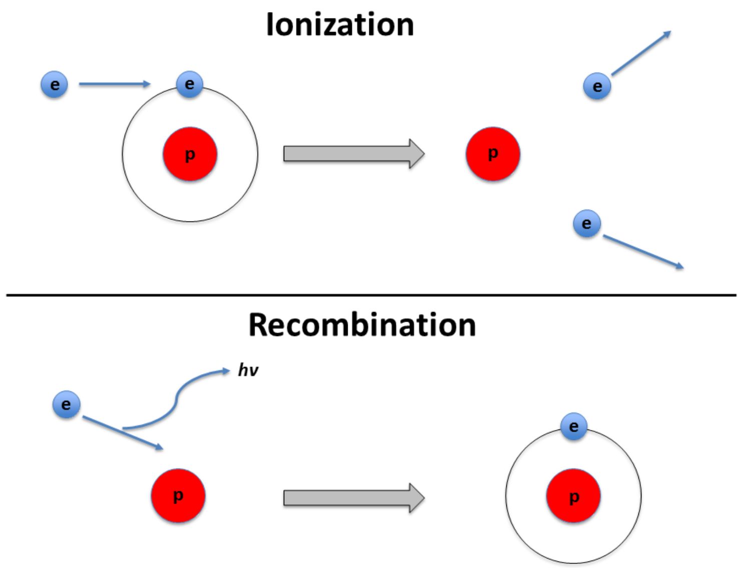

Figure 2.1: Collisional ionization and recombination.

Different chemical elements have different thresholds of energy required for ionization. This ionization energy is what often determines which chemicals will be used for a particular plasma application. For instance, the primary limiting characteristic of electric space propulsion systems is the power system [13]. However, the mass of the gas being used also plays a factor in determining space propulsion system characteristics. The plasma must be expelled at high speed in order to provide sufficient thrust to the system. As such, a balance between ionization energy, propellant mass, and propellant reactivity must be reached. In many space propulsion applications, argon is the gas used as the propellant. As shown in the chart of first ionization energies below, argon has a lower ionization energy than some of the other inert gasses, yet it is massive enough that it can provide sufficient thrust. First ionization energy is the energy required to strip an electron from a gaseous atom, thereby producing an ion with a charge of +1.

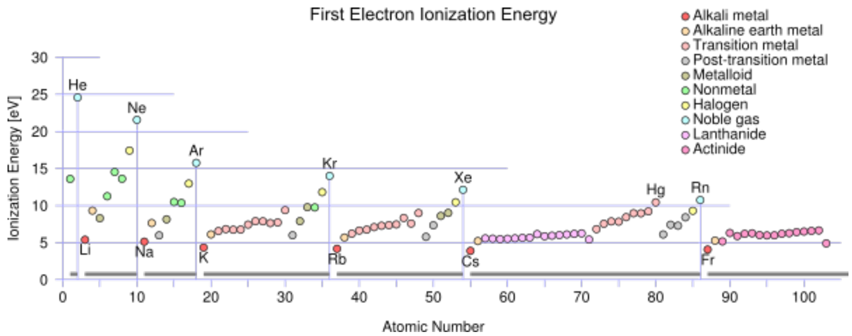

Figure 2.2: First Ionization Energy for periodic elements [14]. Sponk at English Wikipedia. First ionization energy. `http://commons.wikimedia.org/wiki/File:First_Ionization_Energy.svg`, 2015. [Online; accessed April 3, 2015]. Used under fair use, 2015

2.2 Plasma Characterization

There are numerous different types of plasmas all with different characteristics and behaviors. To better categorize plasmas, it is important to understand how they are characterized. Physical properties such as plasma temperature, magnetic field, number density, ionization fraction, and other subsidiary parameters are briefly described in this section.

The most important defining characteristic of a plasma is the plasma temperature. Plasma temperature is essentially the measure of combined particle energy within the ionized gas. Plasma temperature is generally given in electron Volts (eV), where one eV is equal to $1.602 * 10^{-19}$ Joules (J) [12]. The conversion to Kelvin is done by dividing the Joule term by the Boltzmann constant, yielding 11604.5 K. The reason electron Volts are used as the primary unit for plasma temperatures is because it provides a more understandable measure of energy while also simplifying many calculations involved in plasma physics. Since a plasma consists of ions, electrons, and neutral species, it is possible to have a different temperature for each. However, plasmas are often measured and categorized by their electron temperature rather than the ion or neutral temperature since electrons achieve equilibrium faster than ions due to being less massive. Typical plasma temperatures for ETEPS generated plasmas are around 1-5eV. For some context, the temperature of the sun's surface is approximately 0.5eV. Plasmas in the 1-3eV range are generally considered low temperature.

Since a plasma consists of charged particles, it can have a substantial magnetic field **B** associated with it given its movement. The charged component particles are in turn influenced by the magnetic field generated by the plasma as a whole. Quantitatively defining if a plasma is considered magnetized or not can be done in a number of ways, the simplest of which involves measuring the field. In addition, a magnetic vs. non-magnetic plasma can be defined $\omega_{ce}/\nu_c > 1$ where ω_{ce} is electron frequency of gyration and the ν_c is the electron collision rate. The electron frequency of gyration is a measure of how often an electron rotates around a magnetic field. As such, the ratio is essentially a measure of whether or not an electron in the plasma collides with a particle before it completes a rotation. If $\omega_{ce}/\nu_c > 1$ is true, then the plasma is considered magnetized [15]. In ET plasmas, the self induced **B** field is negligible and since ETEPS does not use an externally applied magnetic field, this set of plasma physics can be safely ignored for the purposes of this thesis.

Plasmas consist of three constituent particles: electrons, neutrals, and ions. As such, each of these three particles has a number density, n_e, n_n, n_i respectively, associated with it. Adding these three densities yields an overall number density n, although electron density is often used for characterization purposes. The number density is a measure of the number of particles in a given volume. It is used instead of standard density because the charge of the individual particles generally matters more for plasma applications than mass does. Examples of diffuse plasmas include auroras and nebula with electron densities of $10^{-2} - 10^{3} m^{-3}$, whereas dense plasmas include lightning and stars with electron densities of $10^{18} - 10^{23} m^{-3}$. The electron number densities for ETEPS devices are on the order of $10^{22} - 10^{26} m^{-3}$. Examples of additional plasma densities are available in the Figure below.

It is possible for a plasma to be partially ionized. In fact, the majority of everyday room temperature plasmas such as neon signs and florescent lights are not fully ionized. A gas can

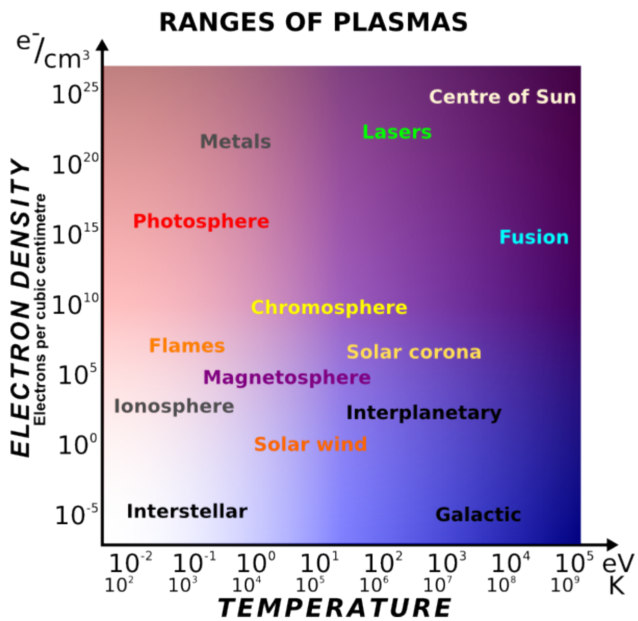

Figure 2.3: Examples of plasma densities and temperatures [16]. Wikipedia, the free encyclopedia. Plasma scaling, 2015. [Online; accessed April 3, 2015]. Used under fair use, 2015

start to display plasma like behavior at as little as 0.1% ionization [12]. For partially ionized plasmas, the ionization fraction and cross-section of neutrals become important characteristics. The ionization fraction determines how much of the plasma consists of neutral species. The neutral species cross-section positively correlates to the magnitude of the collision parameter present in the momentum equation. This collision parameter yields the rate of energy lost due to collisions within the plasma. For the purposes of this thesis, a fully ionized and dissociated plasma is assumed. Partially ionized plasma physics further complicates the modeling and calculations required for preliminary characterization work. The ionization fraction equation is as follows:

$$\alpha = n_i/(n_n + n_i) = n_i/n_0 \tag{2.1}$$

Where n_n is n_0 is the total number of atoms available for ionization. Combining the ionization fraction equation with a perfect gas type equation of state yields the Saha equation, an expression that relates the ionization state to the temperature and pressure of the plasma. The simplified Saha equation for one level of ionization and gas composed of a single atomic species is shown below:

$$\frac{\alpha^2}{1-\alpha^2} = \frac{2}{\Lambda^3}\frac{g_1}{g_0}exp(-\frac{\varepsilon}{k_B T}) \tag{2.2}$$

Where g_1 and g_0 are the degeneracy of the state of the ions, Λ is the thermal de Broglie wavelength, ε is the energy required to remove electrons to create an ion, k_B is the Boltzmann constant, and T is the temperature of the gas.

Additional plasma characterization parameters can be calculated based on the previously described physical parameters. These subsidiary parameters include the Debye length, the Larmor radius, plasma frequencies, velocities, electrical conductivity, and pressures. For this work, the velocities and pressures of the plasma on exit from the ET source are of particular importance. The governing equations for the ETEPS concept are outlined the in the ETFLOW Code Physics section below.

2.3 ETFLOW Code Physics

ETFLOW is a one-dimensional, radially symmetric, time dependent code developed by Bourham et al [17] that is designed to model cylindrical electrothermal plasma sources. It is important to note that ETFLOW was not developed or modified in any way for the purpose of this thesis and was provided and used as is for the work done herein. The code can either be run using ideal or non-ideal conductivity models. The code can also be run in an ablative or non-ablative regime using either solids, liquids, or gases as the source for plasma generation. The simulations for this thesis were carried out using the ideal conductivity model with a non-ablative sleeve and gas as the propellant. The governing physics for ETFLOW will be discussed in this section. The governing continuity equations for ETFLOW consist of the conservation of mass, conservation of momentum, and the conservation of energy equation. The original ETFLOW code was written without energetic material combustion in mind. As such, the code was modified for incorporating the characteristics of combustive materials by Winfrey et al [1]. These modifications are also described below.

The conservation of mass equation is responsible for describing the ablation, erosive burn, and combustive burn effects on the source liner and energetically injected propellant. The ablative form of the conservation of mass equation is shown below:

$$\frac{\partial n}{\partial t} = \dot{n}_a - \frac{\partial vn}{\partial z} \tag{2.3}$$

Where $\frac{\partial n}{\partial t}$ is the rate of change of the particle density, $\dot{n}_a$ is the time rate of change of the number density of the liner due to ablation, $\frac{\partial vn}{\partial z}$ is the rate of change of the particle density with respect to the axial direction z, n is the particle density and v is the plasma velocity. The driver for n_a is the heat flux to the wall of the source:

$$\dot{n}_a = \frac{2q"_{rad}}{H_{sub}A_pR} \tag{2.4}$$

Where $q"_{rad}$ is the radial heat flux directed on the wall of the source, H_{sub} is the energy of dissociation, A_p ionized atom mass, and R is the source capillary radius. For an energetic liner source model such as ETEPS, the ablation of the liner described by n_a must now be modeled as an erosive burn and the conservation of mass equation is rewritten as:

$$\frac{\partial n}{\partial t} = \dot{n}_{a(burn)} - \frac{\partial vn}{\partial z} \tag{2.5}$$

Where $\dot{n}_{a(burn)}$ is the rate of ablated energetic material due to not only plasma ablation, but plasma erosive burn from the radiant heat flux due to the energetic propellant. In order to address the non-ablative regime with energetic propellant, the term's meaning can be changed to n_{burn}, denoting no ablation. Thus, the equation for the non-ablative conservation of mass equation becomes:

$$\frac{\partial n}{\partial t} = \dot{n}_{burn} - \frac{\partial vn}{\partial z} \tag{2.6}$$

The n_{burn} term accounts for the plasma erosive burn to the injected propellant instead of the liner material.

The conservation of momentum equation describes the change in plasma velocity through the capillary in the z-direction:

$$\frac{\partial v}{\partial t} = -\frac{1}{p}\frac{\partial P}{\partial z} - \frac{1}{2}\frac{\partial v^2}{\partial z} - v\frac{\dot{n}_a}{n} - \frac{2\tau_w}{\rho R} \tag{2.7}$$

Where $-\frac{\partial v}{\partial t}$ is the change of the plasma velocity with respect to time, $-\frac{1}{p}\frac{\partial P}{\partial z}$ is the change in velocity due to the axial pressure gradient, $-\frac{1}{2}\frac{\partial v^2}{\partial z}$ is change in velocity due to the kinetic energy gradient, $-v\frac{\dot{n}_a}{n}$ is the velocity loss due to the change in number density, $-\frac{2\tau_w}{\rho R}$ is the velocity loss due to the viscous drag of the plasma along the source liner. The viscous drag is determined by the plasma flow regime, which in turn is determined by the Reynold's number of the flow. The $\dot{n}_a$ term is again present and must be changed to either $\dot{n}_{a(burn)}$ for the ablative regime or $\dot{n}_{burn}$ for the non-ablative regime. Thus, the equation for the non-ablative ETEPS is:

$$\frac{\partial v}{\partial t} = -\frac{1}{p}\frac{\partial P}{\partial z} - \frac{1}{2}\frac{\partial v^2}{\partial z} - v\frac{\dot{n}_{burn}}{n} - \frac{2\tau_w}{\rho R} \tag{2.8}$$

The last continuity equation is the conservation of energy equation given below:

$$n\frac{\partial U}{\partial t} = \eta j^2 - \frac{2q"}{R} - P\frac{\partial v}{\partial z} + \frac{1}{2}\dot{\rho}_a v^2 - \dot{n}_a U - v\frac{\partial vn}{\partial z} \tag{2.9}$$

Where η is the plasma resistivity, U is the internal energy of the atoms in the plasma, and j is the discharge current density. $\frac{\partial v}{\partial t}$ is the change of internal energy of the plasma with respect to time. The joule heating term ηj^2 is the predominant driver of energy change for ablative systems and describes the increase in internal energy due to the heating. $\frac{2q"}{R}$ is the loss of internal energy due to thermal radiation to the source wall, $P\frac{\partial v}{\partial z}$ is the change in internal energy due to the plasma flow work, $\frac{1}{2}\dot{\rho}_a v^2$ is the increase in kinetic energy due to the friction from the ablation process along the wall, $-\dot{n}_a U$ is the loss due to lower temperature ablated particles joining the bulk plasma, and $v\frac{\partial vn}{\partial z}$ is the change in internal energy due to particles passing through the control volume.

The energy equation for an energetic liner propellant is different since the ablated material will release additional material during the erosive burn, thereby increasing the overall change in internal energy. In order to account for the additional energy due to the combustion process, the loss term $-\dot{n}_a U$ can be replaced with a term that describes the combustive energy released by a particle after it ablates from the wall of the source. The new term takes the form $H_{burn}\dot{n}_{a(burn)}$ where H_{burn} is the energy release of the energetic material which is given by the heat of formation. Thus, the new conservation of energy equation can be rewritten as:

$$n\frac{\partial U}{\partial t} = \eta j^2 - \frac{2q"}{R} - P\frac{\partial v}{\partial z} + \frac{1}{2}\dot{\rho}_a v^2 + H_{burn}\dot{n}_{a(burn)} - v\frac{\partial vn}{\partial z} \tag{2.10}$$

The total energy released H_{rel} due to the energetic mass is written as:

$$H_{rel} = \frac{1}{2}\dot{M}_{energy}R_{plasma}H_{form} \tag{2.11}$$

Where $\dot{M}_{energy}$ is the released heat from the energetic mass per unit time in a control volume defined by the plasma capillary radius R_{Plasma}. H_{form} is the heat of formation of the energetic material. These variables can be calculated from the total burned mass by dividing the total released heat by the required sublimation and dissociation molar enthalpy terms. This yields the rate of burn of the energetic mass:

$$\dot{M}_{energy} = 2\frac{f_c(H_{rad}+H_{rels})}{R_{plasma}(H_{vap}+H_{diss})} \tag{2.12}$$

Where H_{vap} is the heat of vaporization, H_{diss} is the heat of dissociation, H_{rad} is the radiated heat, and f_c is the fraction factor of the burn of the energetic mass. The radiated heat can be written as:

$$H_{rad} = f_t\sigma_s(T_{plasma}^4 - T_{vap}^4) \tag{2.13}$$

Where f_t is the energy transmission factor through the vapor shield caused by the burn and gasification of the energetic material, T_{plasma} is the plasma temperature, and T_{vap} is the vaporization temperature.

Chapter 3
Characterization Applications Physics

Although the primary goal of this thesis is to characterize the ETEPS concept, it is a useful exercise to try and understand how such a device can fit into a practical role. Of the numerous roles fulfilled by ET technology, space propulsion and ET weapon systems will be the main focus of this analysis. The roles were chosen due to availability of research on the topics and because at first glance they require very different ET source types and configurations. The basic analytic physics for space propulsion and ET weaponry is provided in this section.

3.1 Space Propulsion

The analysis of electrothermal space propulsion systems requires an understanding of the fundamentals of rocket propulsion. There are three fundamental concepts that effect analysis of rocket propulsion systems: how thrust is produced, how efficiently thrust can be produced, and how thrust and thrust efficiency affect the overall mass of the vehicle [12].

The primary source of thrust for the majority of space propulsion systems comes from the exchange of momentum. Mass is exhausted at a certain velocity and thus has momentum

$$P_{mom} = mv \tag{3.1}$$

Where P_{mom} is the momentum, m is the mass, and v is the velocity. Since the total momentum of a system is conserved, if mass is removed from the rocket with a certain momentum, the rocket must increase its momentum in the opposite direction by an equal amount. Thus the change in the rocket's momentum is

$$dP_{mom} = dmv_e \tag{3.2}$$

where v_e is the exit velocity, dm is a small mass, and dP_{mom} is the change in momentum of the rocket. The change in momentum over a period of time is given by

$$\frac{dP_{mom}}{dt} = \frac{dm}{dt}v_e \tag{3.3}$$

This equation is equal to the momentum thrust F_m, where $\frac{dm}{dt}$ is the mass flow rate of the propellant. Rockets have an additional source of thrust caused by pressure; however, for the purpose of this study, the pressure thrust will be ignored since the ideal case is being assumed.

Another important performance parameter used for analyzing propulsion systems is specific impulse, I_{sp}. Specific impulse takes the thrust and normalizes it by dividing it by the propellant mass flow rate in order to allow different types of propulsion systems to be compared against one another.

$$I_{sp} = \frac{F}{\dot{m}g_0} \tag{3.4}$$

Where g_0 is the acceleration due to earth's gravity at sea level. The term is there in order to make the units for the specific impulse in seconds.

The thrust and the specific impulse are enough for an initial characterization study of a space propulsion system. The ETFLOW code outputs the total mass of the propellant that is ejected in addition to the exhaust velocity of the propellant. These two variables can be used in conjunction with time in order to get a preliminary understanding of the performance characteristics for the ETEPS concept in terms of a space thruster.

3.2 ET Weaponry

To better understand what occurs in the chamber of an electrothermal chemical propulsion system, it is useful to analyze conventional weapon systems in order to see what the drivers behind launch ballistics are. The key variables for launch ballistic characterization are the pressure in the combustion chamber and velocity of the projectile as functions of either the time of projectile travel or the distance of the projectile travel along the barrel. There are two phases for which the physics behind the $P(t)$ and $V(t)$ functions can be divided into: during the propellant burn and after the burn. Since the primary interest of this thesis involves looking at the source only, the after burn phase can be ignored. The driving mechanism behind the pressure buildup in the chamber is the propellant [10]. Since there is no external energy being added to the system, the only energy used for the projectile launch comes from the combustion of the propellant. As such, the propellant combustion can be used to define the pressure present within the gun chamber during the course of the burn. In order to simplify the problem of understanding the forces at hand, the average pressure will be derived in terms of propellant energy allowing the time dependence of the pressure function to be ignored. First, it is assumed that the propellant burns completely. Second, it is assumed that the propellant burn yields an ideal gas which can be used to determine an equation of state:

$$P(V-\eta) = nRT \tag{3.5}$$

Where P is the gas pressure of the propellant combustion product, V is the specific chamber volume, η is the specific covolume of the propellant gas, n is the number of moles per unit weight, R is the gas constant, and T is the temperature at which the combustion occurs. If T_0 is given as the adiabatic flame temperature, the energy of combustion per unit weight of propellant is given as:

$$E_{comb} = nRT_0 \tag{3.6}$$

The E_{comb} term is generally determined experimentally by burning a charge of propellant in a chamber of known volume and measuring the maximum pressure.

During the propellant burn cycle, the gas produced at temperature T_0 is reduced to T due to the transfer of heat to the chamber wall and the work extracted from the expansion of the gas. The change in internal energy per unit mass of gas is given by

$$\Delta I = \bar{C}_v(T_0 - T) \tag{3.7}$$

Where $\bar{C}_v$ is an average value of the specific heat of the gas at constant volume over the temperature range. The quantity $\bar{C}_v T_0$ is the specific energy or potential energy of the propellant. Assuming that the average specific heat at constant volume bears the same relation to the gas constant as the specific heat at constant volume for a perfect gas does, the equation for nR can be rewritten $nR = \bar{C}_v(\gamma - 1)$ where γ is a factor analogous to the ratio of specific heats at constant pressure and volume. Thus, the total energy available from unit mass of propellant can be written

$$E_{total} = \frac{E_{comb}}{\gamma - 1} \tag{3.8}$$

This equation can be taken as an approximation of the internal energy of unit mass of the propellant gas at the adiabatic flame temperature.

The equation of state for the gas in the chamber can be rewritten

$$P(U_g - c\eta) = cnRT \tag{3.9}$$

Where c is the mass of the propellant burned (the total mass of the gas) and U_g is the actual volume of the gas. Given the equation of state, the internal energy of the gas can be written as

$$I = \frac{P(U_g - c\eta)}{\gamma - 1} \tag{3.10}$$

and the general energy equation of interior ballistics can be written as

$$\frac{cE_{comb}}{\gamma - 1} = \frac{P(U_g - c\eta)}{\gamma - 1} + K \tag{3.11}$$

Where K is the energy of the gas expended doing work and transferring heat to the chamber. It is important to note the the given equations use the average pressure and temperatures. In actuality, the pressure and temperature are not uniform throughout the gas and vary as functions of time; however, this average approximation allows the relationships between the internal energy, pressure, and temperature to be understood.

From these equations it is clear to see the importance of the pressure within the chamber for launch ballistics analysis. These same equations can be applied to ETC systems since the work of projectile launch is still done by the combustion product gas of a bulk propellant. It can be argued that the equations given here are actually more appropriate for ETC systems since the burn characteristics are closer to ideal. For the ETEPS concept, the pressure dependence is not only on the burn characteristics of the propellant, but also on the additional energy added to the system by the generation of the plasma. Given the physics presented here, the characterization of the ETEPS concept for a projectile launch system only takes into account the pressure generated over time within the chamber. This is a sound preliminary characterization methodology which will provide a better understanding of the limitations of the ETEPS design.

Chapter 4

ICOPS 2015 - Paper 1399 Manuscript - ETEPS Characterization

The following chapter is a manuscript that has been submitted to the 2015 International Conference on Plasma Science.

Computational Characterization of the Electrothermal Energetic Plasma Source (ETEPS) Concept for High-Enthalpy Flow

Shawn Mittal and Leigh Winfrey

Abstract

The concept of the electrothermal energetic plasma source (ETEPS) involves an energetic gaseous or liquid propellant injection into a confined non-ablative capillary. As the gaseous injection occurs, an arc discharge causes dissociation of the propellant with immediate ionization and combustion. This results in the release of chemical energy and formation of a highly energetic plasma. The ETEPS concept aims to take the electrothermal-chemical (ETC) source concept and eliminate the combustion chamber by combining the plasma generation and chemical release of energy to form a high enthalpy flow. Previous computational work on the ETEPS concept has been conducted using a propellant mixture of ethanol, benzene, and gasoline for a preliminary analysis on the feasibility of ETEPS use for ETC launch systems.

Further computational characterization is useful to fully understand the abilities and limitations of the ETEPS concept. A characterization study has been conducted for the ETEPS concept using the electrothermal plasma code ETFLOW. This study presents the results for the ETFLOW code using Hydrazine, Butane, and Acetylene for 30kA, 20kA, and 10kA current pulses over

130μs. Results show that practical applications for ETEPS are not limited to only ETC launch systems but have many other applications including space propulsion and direct launch systems.

4.1 Introduction to ETEPS

The electrothermal energetic plasma source (ETEPS) concept was first proposed by Winfrey et al [1] in 2014 and differs from conventional capillary discharge electrothermal source designs in that it uses an energetic propellant in order to generate a plasma. Whereas conventional capillary discharge devices generally use a non-energetic ablative liner such as Lexan [18] for the plasma generation, ETEPS uses combustible materials. The large propellant selection in turn allows for a large range of operating parameters based on the various kinds of propellants used. To further add to the operational range, the ETEPS concept has two distinct modes of operation, an ablative mode in which the capillary liner material is the energetic propellant, and a non-ablative mode in which a gas or liquid propellant is injected into the capillary prior to the current arc discharge. The liner in the non-ablative ETEPS concept does not add particles to the plasma that is generated.

Previous characterization work done with the non-ablative ETEPS concept was done using a configuration where the source was filled with a 90%/5%/5% mixture of ethanol/benzine/gasoline and powered using a 20μs pulse with a 45kA peak current [1]. A peak pressure of 190 MPa with peak bulk velocity of 7 km/s was observed. In addition, peak temperature was 2.48eV and the maximum radiant heat flux was 24.13GW/m^2. Similar results are seen in this characterization study; however, a number of different current profiles are used in order to further aid in analysis.

As shown in previous characterization work, there are a number of applications for which the ETEP source would be well suited. The results of computational testing with Hydrazine, Butane, and Acetylene show that the ETEPS concept has applicability for ETC, direct launch, and space propulsion systems. By varying the current pulses and the propellants, a large array of plasma parameters can be reached.

Although this study is somewhat limited in scope, its purpose is to serve as a starting point for further characterization work. In addition, several potential trends that warrant further study have been shown regarding the impact of varying current pulse through an ETEP source.

4.2 ETFLOW Code

The ETFLOW simulation code used has been used for numerous characterization studies for the analysis of electrothermal sources [19, 20, 21, 22]. It is a one dimensional, time dependent code developed for the purpose of modeling a large variety of capillary style electrothermal devices. The plasma is modeled using a single fluid model. The preliminary ETEPS concept analysis was done using a modified version of ETFLOW which is sometimes designated ETFLOW-EN. The work presented here is done using the same modified code. Modifications to the code are discussed extensively elsewhere [1].

Inputs to the code include source geometry, source material, current pulse profile, and propellant gas. The injection of the gas into the source is not modeled; as such, the gas is stationary at the start of the simulation. In addition, an ideal conductivity model was used in order to simulate the plasma flow through the source. A current limitation of the ETFLOW code is that the volume of the propellant gas is dependent on the source geometry and cannot be varied independently. However, since the source geometry was not varied for this study, this limitation can be ignored.

The simulations were run using three different current pulse profiles of 30kA, 20kA, and 10kA all discharged over a $130/mu$s pulse. The current pulse profiles are shown in Fig. 1. Each of the three profiles was run using Hydrazine, Butane, and Acetylene while keeping the source geometry constant. Additional constants include the non-ablative source liner material and the use of the ideal conductivity model. Table 1 shows the source geometry information.

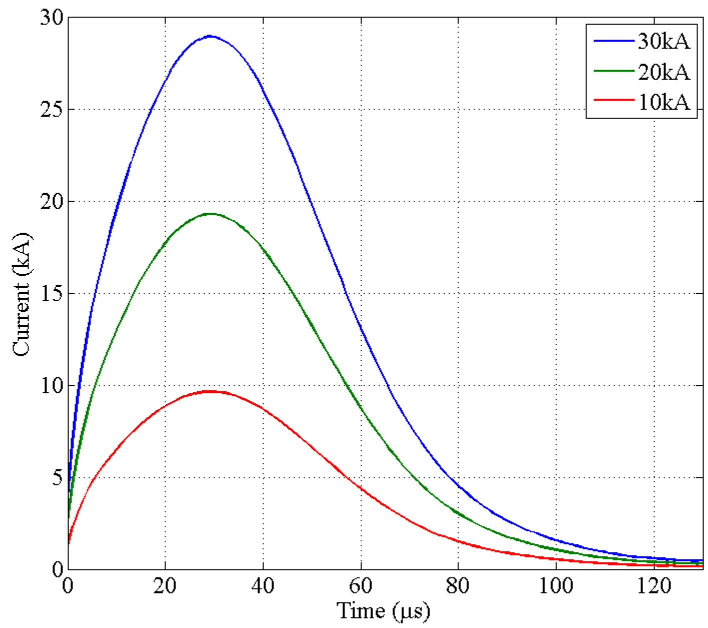

Figure 4.1: Current Pulses used for simulation.

4.3 Results and Discussion

Plasma temperatures on the order to 1.32 - 2.09eV, heat fluxes of 2 - 12GW/m^2, exit pressures of 65 - 372.9MPa, and bulk velocities of 1 - 6.46km/s were seen.

The combined exit pressures for all of the cases run can be seen in Fig. 2. As expected, the current pulses of higher magnitude yield higher pressures; however, it is interesting to note the large range over which the pressures vary. The highest pressures were reached by the butane with a 30kA pressure of 372.9MPa while the lowest pressure was reached by acetylene at 10kA with 65MPa. The differences in the exit pressures seem to be influenced heavily by the magnitude of the current pulse. Fig. 2 shows a larger variation between the three gases for the 30kA pulse and a much smaller variation for the 10kA pulse.

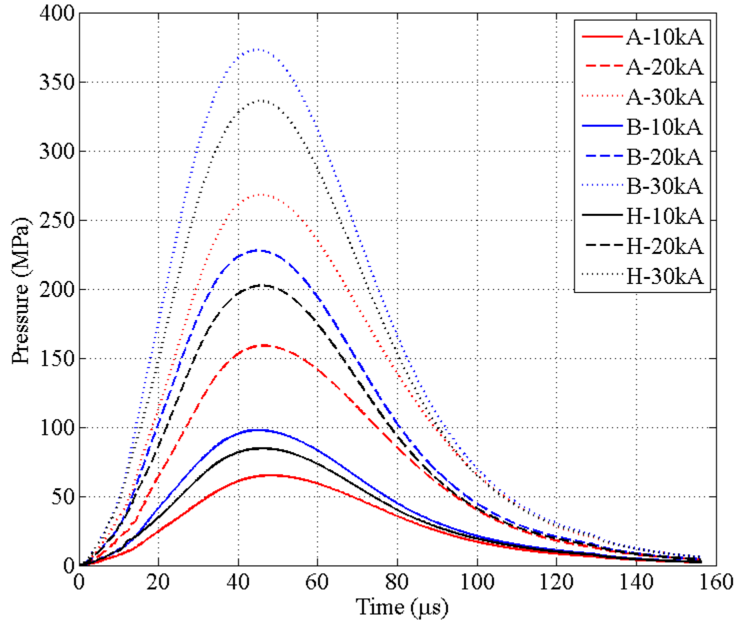

Figure 4.2: Exit Pressure vs. Time for Hydrazine, Butane, and Acetylene

Variance in bulk velocity is not as dependent on the current magnitude. This trend can be seen in Fig. 3. The highest bulk velocity of 6.46km/s was reached by butane. Although the lowest bulk velocity of 4.8km/s was achieved using acetylene, the gas shows the most dependence on current magnitude yielding a ΔV_{bulk} of 0.934km/s compared to the 0.909km/s and 0.864km/s for the hydrazine and the butane respectively.

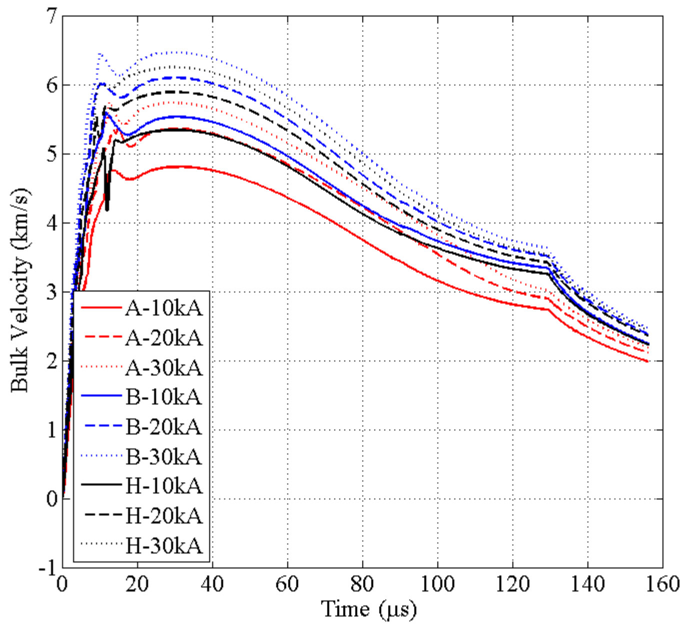

Figure 4.3: Bulk Velocity vs. Time for Hydrazine, Butane, and Acetylene

As expected, the radiant heat flux is highly dependent on the current magnitude; however, the degree to which different gases are effected was not expected. This trend can be seen in Fig. 4. The 30kA hydrazine case yielded the highest heat flux of 11.71GW/m^2 while the 10kA case yielded 3.69GW/m^2 with a difference of 8.02GW/m^2 between the two values; however the difference for the 30kA and 10kA butane cases was only 3.59GW/m^2.

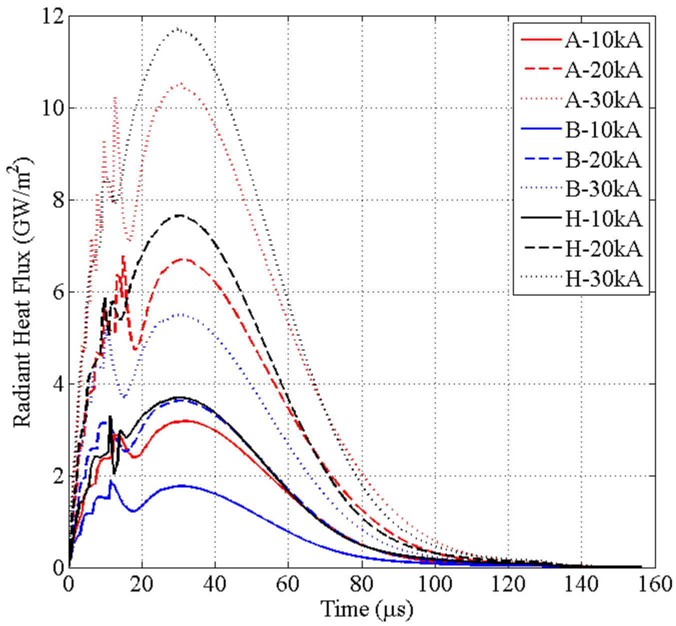

Figure 4.4: Radial Heat Flux vs. Time for Hydrazine, Butane, and Acetylene

Fig. 4 and Fig. 2 show that butane ETEP source would be ideal for an application requiring high exit pressures, but low radial heat flux. For instance, if used in a direct projectile launch application, the heat being deposited to the walls of the launcher could be minimized while still maintaining sufficient launch ballistics. This idea is better illustrated by Fig. 5. which compares the radial heat fluxes of the three gases tested and their exit pressures. For an application such as an electrothermal chemical ignition system which requires higher heat fluxes for a given pressure, a gas such as acetylene may be better suited for the role.

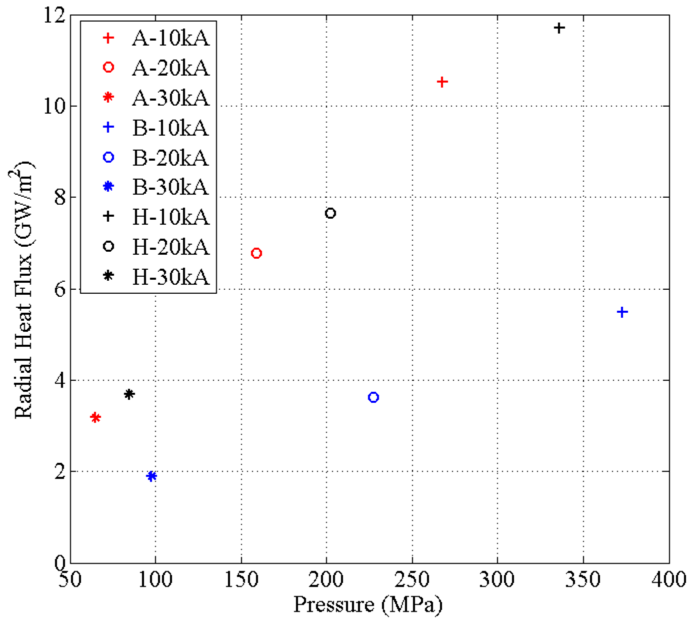

Figure 4.5: Radial Heat Flux vs. Pressure for Hydrazine, Butane, and Acetylene

Fig. 6 shows the bulk velocity and 10kA pulse over time for the acetylene case. Since ll of the cases run have a similar relationship between bulk velocity, current, and time, only a single case was chosen for the figure. The bulk velocity shows a dependence on the current pulse ramp up, reaching its peak value at the current pulse peak; however, the velocity reduction occurs at a much slower rate. This is most likely due to the pressure buildup that occurs in the confined capillary. The pressure keeps the plasma ejecting out of the source at an elevated rate even after the current pulse subsides.

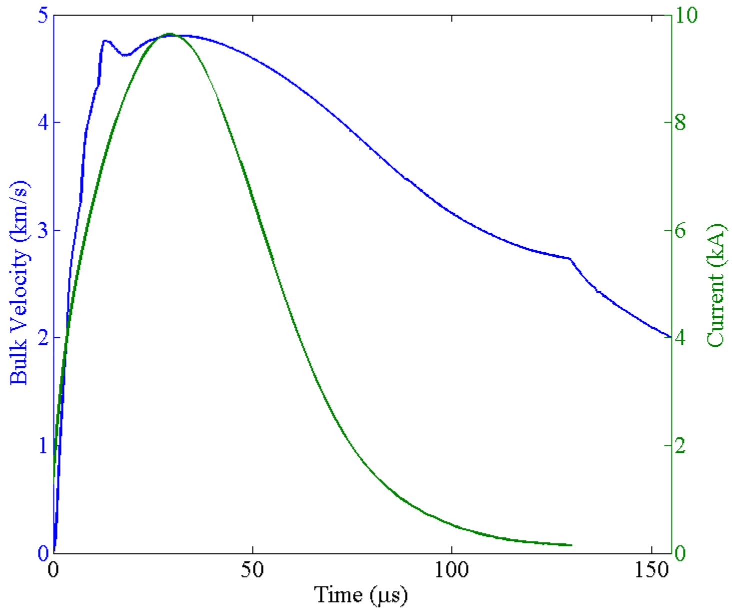

Figure 4.6: Velocity and Current vs. Time for a 10kA acetylene pulse.

The maximum temperature of 2.09eV was reached by the 30kA hydrazine case and the lowest was reached by the 10kA butane case. Fig. 7 shows the evolution of temperature vs. time for all of the cases studied. Interestingly, although the butane temperature was the lowest of the three gases, the butane case exit pressures were the highest. This is the same relationship demonstrated by the heat flux and the pressure.

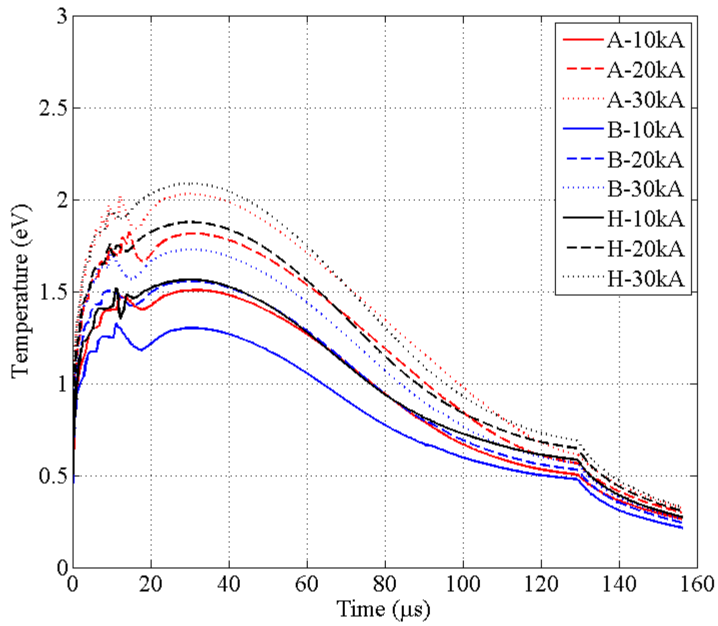

Figure 4.7: Temperature vs. Time for Hydrazine, Butane, and Acetylene

4.4 Conclusion

The electrothermal energetic plasma source (ETEPS) has been further investigated using the ETFLOW code. The code was used to test three gases: hydrazine, butane, and acetylene using three difference current pulse profiles. Butane produced the highest pressure at all current magnitudes, while also producing the lowest radiant heat fluxes and temperatures. The high heat flux and pressure cases demonstrated in this study show promise for ETC ignition systems. In addition, the high pressure low heat flux and temperature cases show potential applicability for direct launch systems where high heat transfer to the projectile and launch system walls is not desired. All cases provide a sufficient bulk velocity and mass ejection for use as space propulsion sources; however, the lower current cases are most likely better suited for such use.

Further characterization work with a focus in each of the applications is needed in order to better understand the capabilities and limitations of the non-ablative ETEPS concept; however, the tested cases show that it is capable of producing a wide range of plasma parameters suitable for a number of uses.

Acknowledgment

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Chapter 5
ICOPS 2015 - Paper 1669 Manuscript - ET Weaponry

The following chapter is a manuscript that has been submitted to the 2015 International Conference on Plasma Science.

Computational Study of Real Time Modification for Electrothermal Gun Ballistics

Shawn Mittal and Leigh Winfrey

Abstract

Current gun technology uses solid propellants that consist of small geometrically similar grains which are ignited by a primer. Propellant burn characteristics are determined by a combination of the chemical propellant itself and grain geometry. The ballistic characteristics of a preformed cartridge cannot be changed in real time. Thus, varying applications require the use of different projectiles, propellants, and launch systems.

Much of the study regarding electrothermal (ET) systems in gun technology involves using plasma as an ignition source for a bulk propellant in order to obtain improved burn characteristics for chemical propellant. Pure ET guns attempt to replace chemical propellant with an electrothermal launch system in which the plasma itself is the working fluid responsible for propelling the projectile.

This study takes the electrothermal energetic plasma source (ETEPS) concept and computationally characterizes ballistics performance data for projectile launch using a single source con-

figuration with varying current pulse inputs. The data is then compared to known ballistics data for current conventional small caliber gun systems in order to demonstrate the validity of the ET gun technology analyzed in this study.

5.1 Introduction

Electrothermal technology in projectile launch systems has been largely investigated for use in electrothermal-chemical (ETC) launchers [23, 24, 25, 26, 27]. The purpose of the plasma in this application has been to control and enhance the burn rates of a bulk propellant which generally consists of conventional solid propellants. The ET source in this type of configuration is generally placed in the breech of the gun, where it acts as an ignition source. This technology along with conventional gun technology is limited by the fact that launch ballistics are controlled largely by the propellant composition and burn characteristics [10]. Although ETC systems allow for a larger degree of control over burn characteristics than conventional systems, they still lack the ability to significantly change launch ballistics at the push of a button.

Electrothermal launch systems, where the plasma is the working fluid, have the capability to provide a larger degree of control over the pressure gradient and propellant exit velocities within the gun combustion chamber. In addition to the use of non-energetic gases as the propellant gas in an ET system, chemically energetic gases can also be used. This concept is known as the electrothermal energetic plasma source and allows for the harnessing of the chemical energy of the propellant in addition to the electrical energy of the plasma. The ETFLOW simulation code used for this study is designed for the purpose of analyzing the ETEPS concept.

The ETEPS launch system concept presented herein attempts to obtain chamber pressures similar to those of multiple small caliber weapons systems in order to demonstrate the feasibility of using an electrothermal plasma source as an adaptable launch system capable of on the fly modifications to launch ballistics. The conventional gun systems that will be used for comparison purposes are the 5.56mm Ball M193, the 7.62mm Ball M80, and the 20mm M56A3. The projectile chamber parameters, volumes, and bore areas are shown in the table below.

Table 5.1: Projectile Chamber Parameters

Projectile	Chamber Volume (in^3)	Bore Area (in^2)	Chamber Pressure (kpsi)
5.56mm M193	0.109	0.0377	47.8
7.62mm M80	0.189	0.0732	49.7
20mm M56A3	2.70	0.515	47.3

5.2 Simulated Electrothermal Source

The ETEPS source concept analyzed within this paper operates in the non-ablative regime using an injected gas for the propellant as illustrated by Figure 1. As seen in the figure, closing the switch discharges the current through the source chamber. This action is preceded by an injection of gaseous propellant which is ionized due to the arc. The concept is similar to that of an arcjet; however, the mode and parameters of operation differ greatly. In addition to propellant ionization, combustion of the propellant also occurs. As such, bulk exit velocity and chamber pressures are generally higher than conventional ET systems.

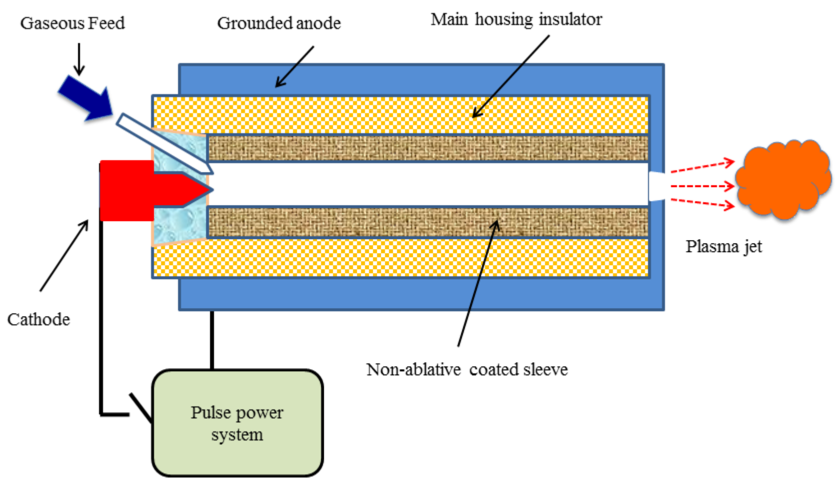

Figure 5.1: Nonablative electrothermal plasma source with gaseous injection.

Since both the injection system and the current input can be controlled, this system allows for a high degree of flexibility for the control of launch ballistics. Figure 2 shows how this concept might be implemented in a full scale gun. The ET source itself acts as the combustion chamber for the gun. Such a system may have the ability to replace the barrel in order to accommodate different types of projectiles and address barrel erosion problems. The figure also shows the gas injection and electrical components of the gun system. It is important to note that neither of these systems are modeled in the ETFLOW code.

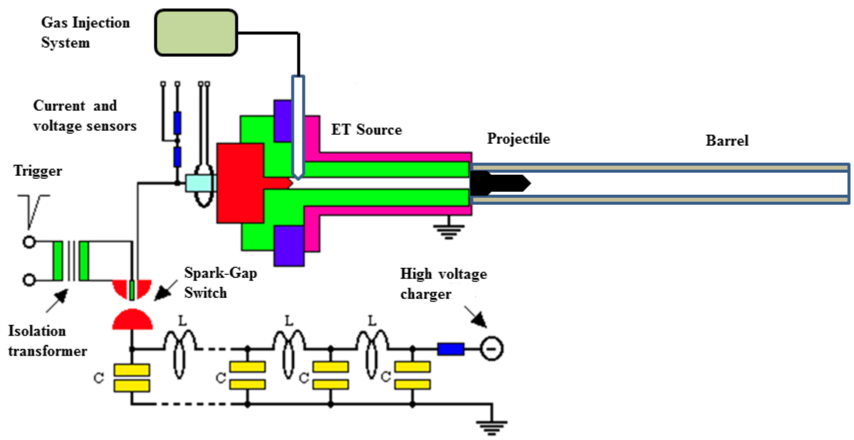

Figure 5.2: Non-ablative electrothermal plasma launcher.

The propellant gas can either be non-energetic, such as argon or hydrogen, or energetic, such as hydrazine or another combustible of some sort. The arc dissociates the propellant leading to immediate ionization and combustion. The plasma at exit of an ETEP source consists of both combusted and non-combusted species.

5.3 Simulation Code Overview

The code used to simulate the ETEP source is called ETFLOW. It is a 1D, time dependent simulation code developed to model a variety of electrothermal sources in multiple geometric configurations with various materials. A single fluid model is used to describe the plasma. The code has been used in several studies for modeling both ablative and non-ablative capillary discharge for a number of different applications [19, 20, 21, 22]. The original code has been experimentally verified by Winfrey et al. [18]. In order to properly address the physics for a non-ablative gaseous plasma discharge for energetic propellant, the set of governing equations has been modified. The modifications to the code are discussed extensively elsewhere [1].

The version of ETFLOW used for this study is a source only code that takes inputs for a cylindrical source geometry, source material, current pulse profile, and propellant gas. It is important to note that at this time, the gas is modeled as stationary at the start of the simulation. An additional limitation of the current ETFLOW code is that it isn't possible to specify the volume of the gas present within the source. The propellant being used occupies the internal cylindrical area of the source being used. However, since the focus of this study is to demonstrate the validity of changing exit pressures based on current profiles, this does not pose a problem in the analysis.

5.4 Simulation Parameters

The ETFLOW simulation code was run with six different current pulse profiles using Hydrazine for the ETEP source propellant. The profiles are broken into long pulse lower current pulses that have a discharge time of 130μs and short pulse higher current pulses that have a discharge time of 20μs. These profiles were selected in order to observe how a variety of current discharge schemes impact the chamber exit pressure profile. The short pulse profiles can be seen in Figure 3 and the long pulse profiles can be seen in Figure 4. The Hydrazine propellant was run through 12cm and 8cm long sources for each current profile. Additional details about the source geometry can be found in Table 2. As seen in Table 2, the source volumes and exit areas are similar to the chamber volumes and bore areas for the conventional weapons systems shown in Table 1.

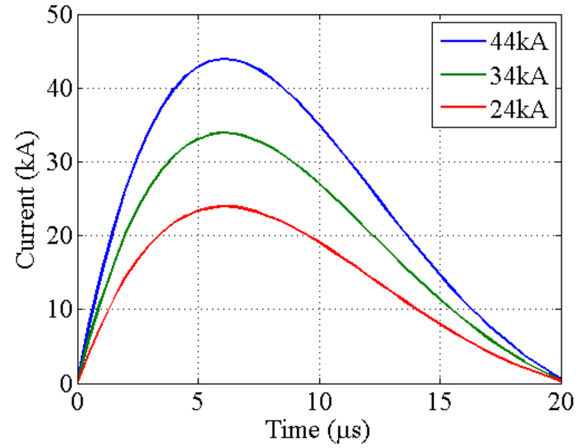

Figure 5.3: Short current pulses used for simulation.

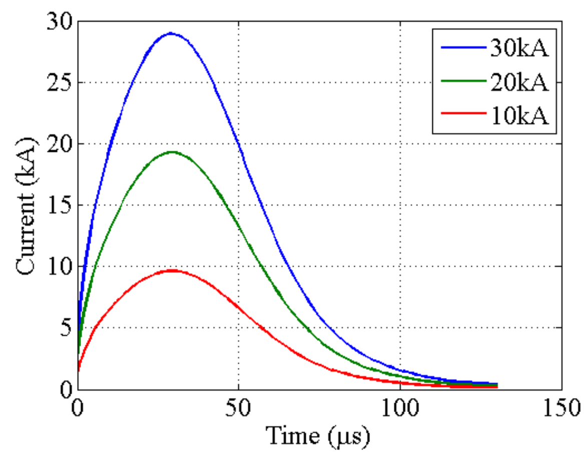

Figure 5.4: Long current pulses used for simulation.

The fixed parameters in the source include the source wall and liner material which was simulated as Lexan. Since the code was run in a non-ablative configuration, the ablative plasma contribution of the wall and liner material can be ignored. The radial source geometry and propellant was also kept constant.

Table 5.2: Geometric Source Parameters

Source Length (cm)	Source Volume (in^3)	Exit Area (in^2)
8	0.2932	0.0621
12	0.1955	0.0621

5.5 Simulation Results

The chamber exit pressure results for the long current pulses are shown in Figures 5 and 6. Given the geometrical source configurations and long current pulse profiles tested, the ETEP source using Hydrazine as a propellant has been demonstrated to have a chamber exit pressure range of 411.13MPa - 77.86MPa. This compares favorably with the three conventional gun systems shown in Table 5.1. The results show that the use of multiple source geometries and current pulses provides a large number of operational ranges suitable for multiple launch applications. The shortened 8cm source chamber volume of 0.1955 in^3 is very close in size to the 0.189 in^3 volume of the 7.62mm Ball M80 round.

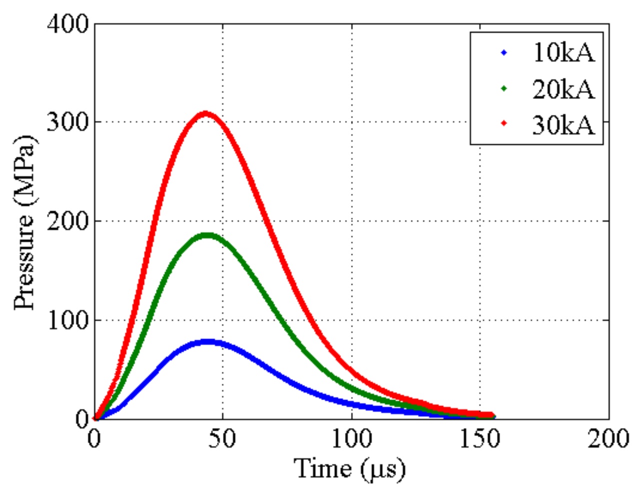

Figure 5.5: 8cm Long Pulse Source Pressure vs. Time.

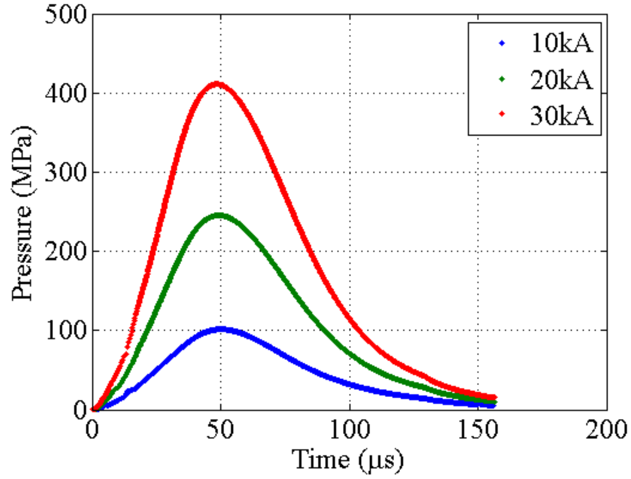

Figure 5.6: 12cm Long Pulse Source Pressure vs. Time.

The chamber exit pressure results for the short pulses are shown in Figures 7 and 8. Although the exit pressure profiles were not fully computed beyond approximately 24 seconds, the maximum pressures were still able to be obtained from all of the simulated shots. Interestingly, the source length seems to have less of an impact on exit pressure when using short current pulses of 20μs. This may be due to incomplete combustion and ionization of the propellant over a short pulse discharge. The max pressure range for the short pulses given both source geometries was 258.52MPa - 106.66MPa. Although the difference in current for both the long and short pulse configurations was 20kA, the variance achieved in exit pressures for the long pulse discharges was significantly greater.

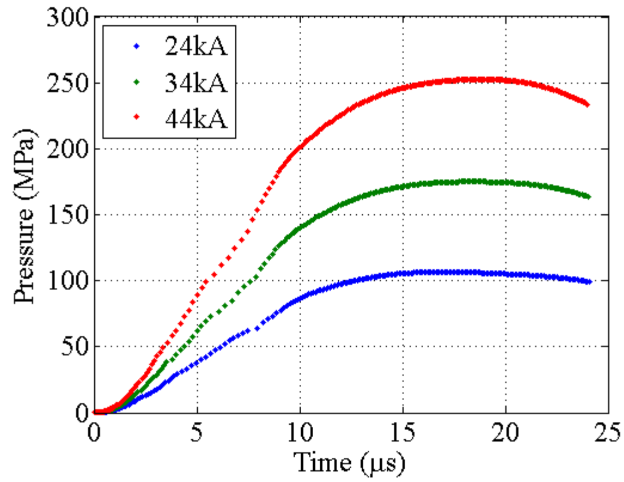

Figure 5.7: 8cm Short Pulse Source Pressure vs. Time

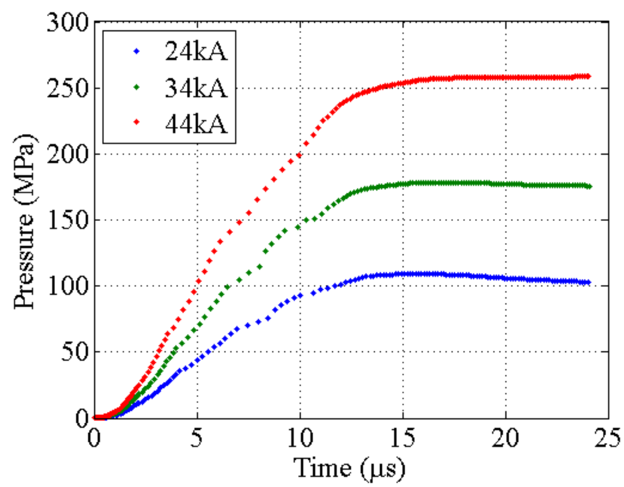

Figure 5.8: 12cm Short Pulse Source Pressure vs. Time

5.6 Conclusion

The exit pressure results for all of the source and current pulse configurations are well within the range of operation for use as projectile launch systems. The possibility of using a single system with a single propellant to obtain a variety of pressure profiles and maximum chamber pressures demonstrates the adaptability of such a design. Given the results of this computational analysis, the ETEPS concept deserves further study as a potential replacement for multiple small caliber weapons systems in use today. Due to the limitations in power systems, ETEPS is not a one stop solution for all roles fulfilled by conventional weapons systems; however, its adaptability makes it worth further study.

Chapter 6
Design and Development of the ETEPS Concept

Given the promising computational results of the two studies conducted for the non-ablative electrothermal energetic plasma source, the next step in analysis is to build a functional device that can experimentally verify the data. The process for data verification will include the use of traditional plasma diagnostics such as invasive probes in the path of the plasma discharge as well as novel optical electrothermal capillary discharge analysis techniques developed by Matthew Hamer [28]. The configuration for the experimental work will be the ETEP source with the discharge opening in a vacuum chamber. The electrical, and injection systems will be attached to the source on the outside of the vacuum chamber. The design of the ETEPS device can be broken down into three main components, the ETEP source, the injection system, and the power system. The design of these components will be discussed in this section.

6.1 ETEP Source Design

The design for the ETEP source was largely based on the design for an ablative electrothermal source by Trey Gebhart that is being used to study fusion reactor refueling with ET guns. Gebhart's design documentation is currently unpublished; however, the source design is very similar to that of the SIRIN source created for the Department of Defense in 1987 [17]. Since the original design uses the ablation of lexan as the primary source for the plasma particles, some changes had to be made in order to allow for gas injection. In addition, the choice was made to forgo using a non-ablative material and keep lexan as the source liner due to costs. Although this decision will complicate experimental verification of the non-ablative ETEPS data, it will still allow for order of magnitude verification. A baseline discharge can be conducted without gas injection in order to ascertain the impacts of the ablative lexan sleeve. The dual ablation and gas injection design can also be studied as a concept unto itself for future work.

The source itself consists of six individual components: the ground housing, liner, insulating sleeve, electrode, feedthrough, and the gas flow nozzle. The cad drawing of the assembled ETEPS is shown in Figure 6.1 below. The source has a length of approximately 8.03 inches with an approximate diameter of 2.5 inches.

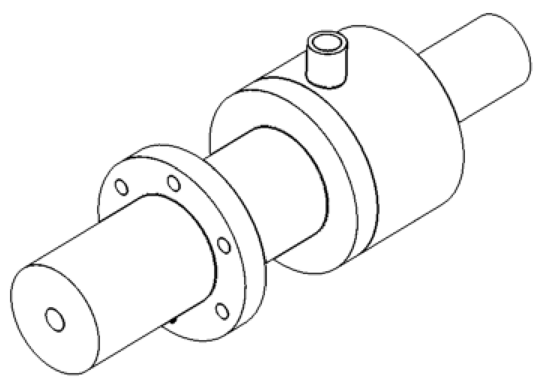

Figure 6.1: CAD drawing of assembled electrothermal energetic plasma source.

Of the six components that make up the source, the ground housing, electrode, and feedthrough can be interchanged with the ablative ET source designed by Gebhart, allowing for limited parts compatibility between the two systems. The ground housing acts as the anode of the system shown in Figure 5.1 while the electrode and the feedthrough act as the cathode. These three components are shown in relation to one another in the figure below.

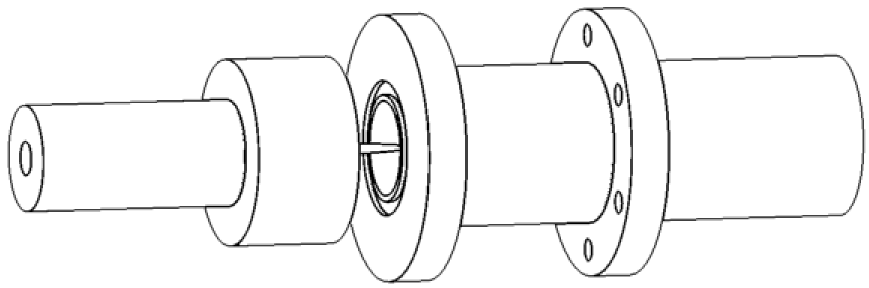

Figure 6.2: The electrode, feedthrough, and ground housing of the ETEP source.

The liner, insulating sleeve, and gas flow nozzle are all made out of lexan and are considered destructible parts with a limited number of uses possible. The gas flow nozzle and liner fit into the insulating sleeve allowing their geometry to be modified without having to redesign the system. This variability allows for testing the impact of changing geometry on the plasma characteristics in order to better match the ETFLOW code inputs. The gas flow nozzle and the liner are shown in Figure 6.3 while Figure 6.4 shows the insulating sleeve as well.

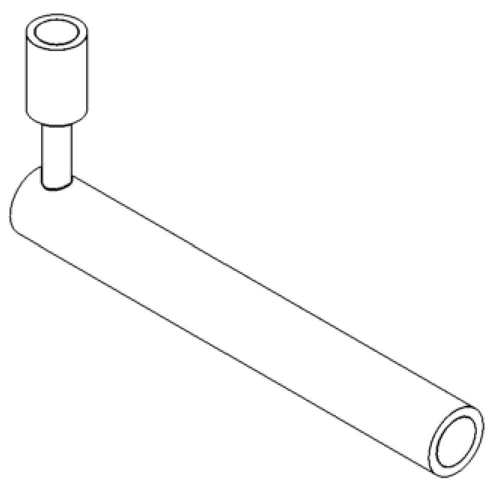

Figure 6.3: The liner and the gas flow nozzle. The liner has a hole in it to allow for the injection of the propellant.

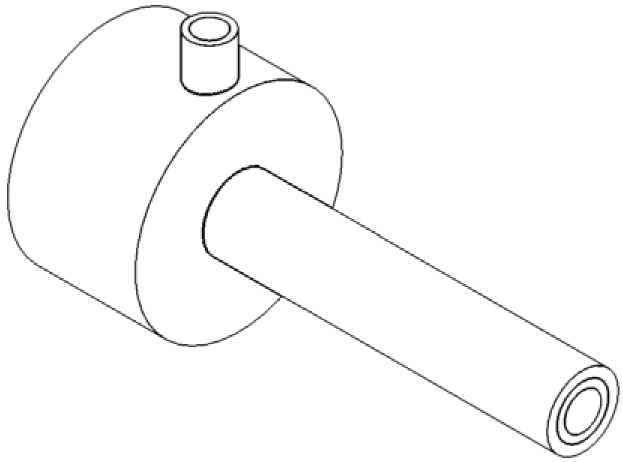

Figure 6.4: The liner and the gas flow nozzle with the insulating sleeve.

The liner has a diameter of approximately 1.11cm and length of 12cm, yielding a combustion chamber volume of 11.658cm^3. The reason the source was designed with a chamber volume larger than the sources tested in the ETEPS characterization papers is due to the fact that initial testing of the experimental ETEP source will occur with a larger injection of gas in order to allow for errors in gas injection timing and ignition of the source. The large chamber area allows for greater error in the injection process. The machining of the ETEP source components has been completed and the source components are shown in figure 6.4 below. The ground housing, electrode, and feedthrough are made of copper.

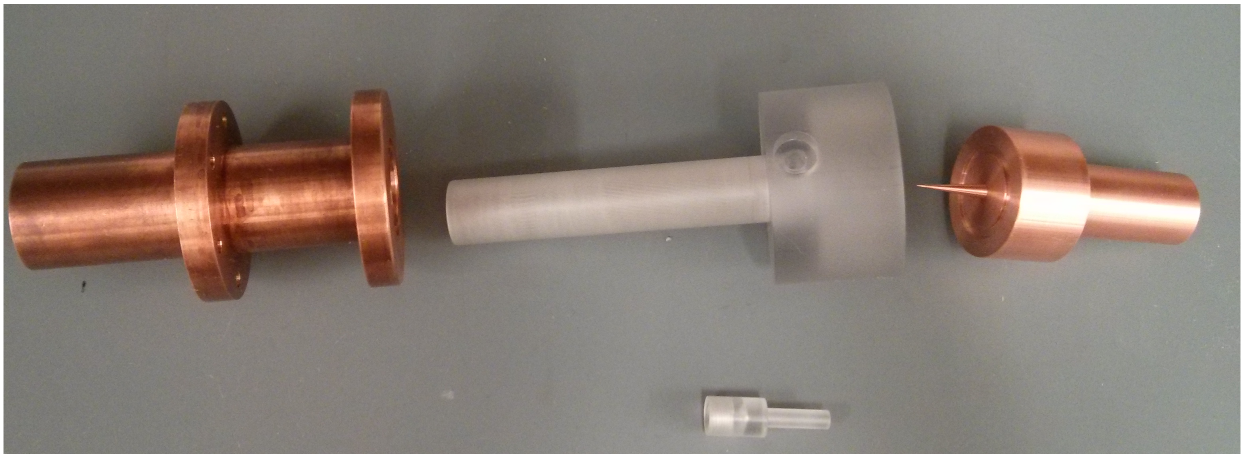

Figure 6.5: The fully machined ETEP source.

6.2 ETEPS Injection System

The injection system for the ETEPS design consists of a propellant tank, a regulator, a solenoid valve, and the gas flow nozzle. The flow diagram is shown in Figure 6.6. In order to understand how the pressure and nozzle geometry impact the mass flow rate of the propellant, the injection system was mathematically modeled. The physics behind the mathematical model is exactly the same as that used for zero dimensional analysis of a cold gas thruster. As such, the injection system model presented here is only a rough representation of what can be expected in terms of flow conditions and must be experimentally verified. The source pressure and regulator pressure are used in order to compute the mach number of the propellant flow

$$\frac{p_{exit}}{p_{reg}} = (1+\frac{\gamma-1}{2}M_{exit}^{2})^{\frac{\gamma}{1-\gamma}}) \tag{6.1}$$

Where p_{exit} is the pressure at the nozzle exit (the source chamber pressure), p_{reg} is the regulator pressure, γ is the specific heat ratio of the propellant gas, and M_{exit} is the mach number at nozzle exit. Based on M_{exit}, a characteristic exhaust velocity can be determined via

$$c = \frac{M_{exit}\sqrt{\gamma RT}}{\gamma(\frac{2}{\gamma+1})^{\frac{\gamma+1}{2\gamma-2}}} \tag{6.2}$$

Where R is the gas constant of the propellant gas and T is the gas temperature. From here, the mass flow rate can be determined via

$$\dot{m} = \frac{A_{exit}\,p_{reg}}{c} \tag{6.3}$$

Where A_{exit} is the nozzle exit area. Using the mass flow rate it is possible to estimate the amount of time the solenoid valve should be opened for in order to allow in the desired amount of propellant.

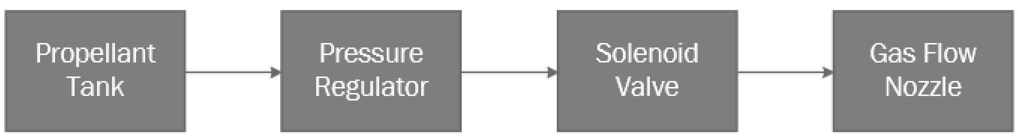

Figure 6.6: Injection system flow diagram.

6.3 ETEPS Power System

It is important to note that the power system that will be used for the experimental testing the the ETEPS concept was designed for use with the electrothermal ablative plasma source mentioned before. This pulsed power system is again based on the work done for the SIRIN source created for the Department of Defense in 1987 [17]. The power system components consist of a 10kV DC power supply, a 340μF capacitor, three charging/discharging interlocks consisting of relays, a relay controller, a spark gap switch, 100kΩ ballast charging resistors, a signal generator, a pulse shaping inductor, a delay generator, and a high voltage trigger. The system has a maximum possible energy of 17kJ with a maximum current peak of 100kA. The pulse length can be varied with length on the order of 50 - 150μs. The power delivery system schematic is desplayed in Figure 6.7 below.

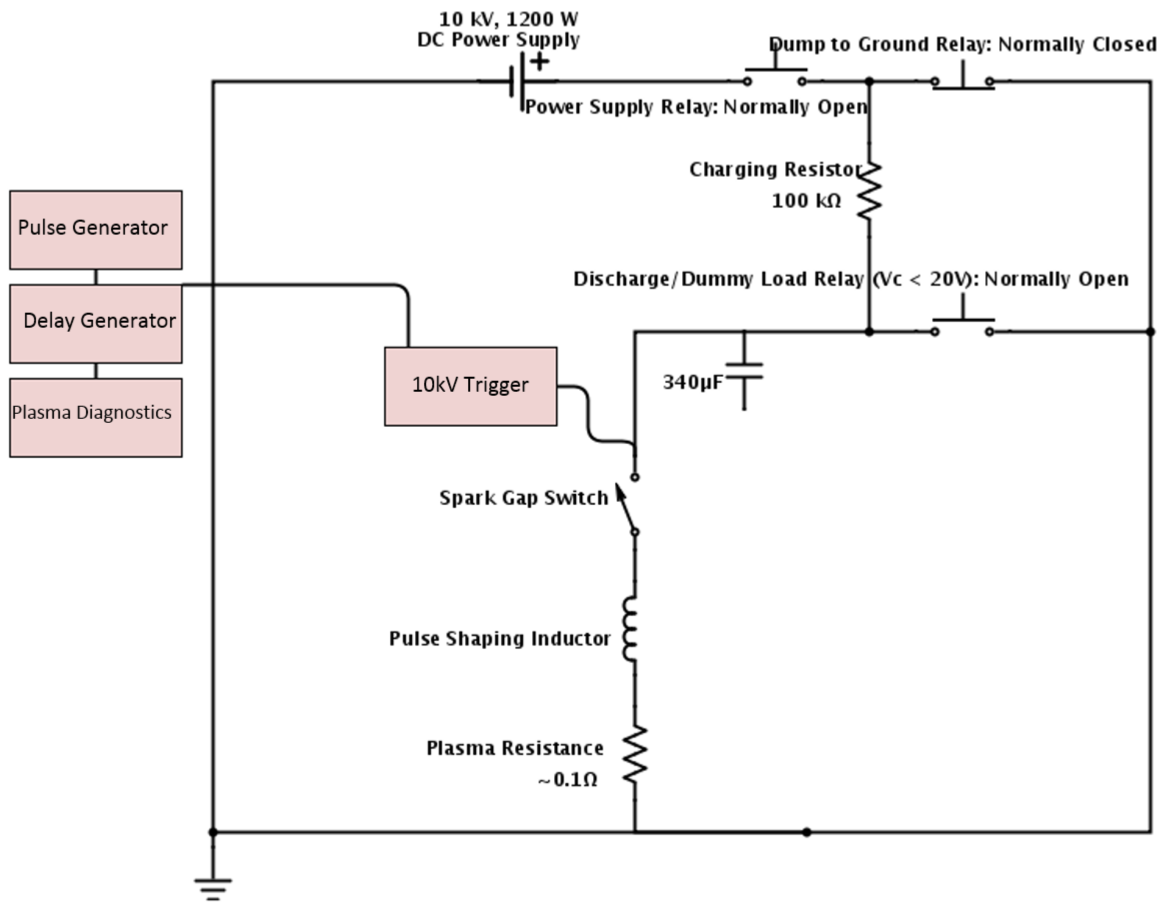

Figure 6.7: ET pulsed power delivery system schematic.

Chapter 7
Conclusion and Future Work

7.1 Conclusion

The purpose of this study was to characterize a new electrothermal source concept introduced in 2014 known as the non-ablative electrothermal energetic plasma source. In order to provide context for potential applications of the ETEPS concept, the design was characterized within the parameters of a space thruster and an electrothermal gun. The exit velocity, pressures, heat flux, and plasma temperatures in the two computational studies conducted show that the ETEPS concept is indeed a viable option for both of the aforementioned applications.

For current pulses ranging from 10 - 30kA over 130μs, the ETFLOW code showed plasma temperatures on the order to 1.32 - 2.09eV, heat fluxes of 2 - 12GW/m^2, exit pressures of 65 - 372.9MPa, and bulk velocities of 1 - 6.46km/s using hydrazine, acetylene, and butane. Hydrazine was chosen to further characterize the ETEP source for use as an ET weapon system. Using the ETEPS design for direct projectile launch applications allows for an incredible amount of control over launch ballistics of the projectile. Launch ballistics can be changed in a way that cannot be done with conventional systems or even electrothermal-chemical systems.

In order to facilitate further study on the ETEPS design and to provide experimental verification of the ETFLOW code, a gas injection plasma source was designed. The design has parts compatibility with other systems currently being used in the B and E Applied Sciences (BEARS) Lab at Virginia Tech for which the ETEP source was designed. Further, the ETEPS design uses a pulsed power electrical system that will also be used for other electrothermal plasma systems. The power system is fully capable of providing the current pulse profiles studied in the characterization work. The ETEP source design is modular in nature allowing for a variety of geometric configurations to be tested for experimental verification of the ETFLOW code. In addition, the gas flow nozzle can easily be changed, allowing for further research into the gas injection design.

7.2 Future Work

Although the source has been designed, it has not yet been tested. Experimental work must be conducted on the ETEPS design in order to verify not just the ETFLOW code, but also the construction of the device itself. In addition, further characterization studies should be conducted using more current pulse profiles, source geometries, and propellant gasses. The work presented in this thesis is just the start of the research that needs to take place on the ETEPS concept before it can see use in real world applications. The data collection for the experimental ETEPS design is also an area that requires further study. There are a number of optical and intrusive methods for plasma data collection which can be used for the purpose of experimental plasma characterization. These methods must be looked into and assessed for use with the ETEPS design.

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