Abstract—Theoretical calculations are performed with a one-dimensional (1-D), steady state, isothermal computer plasma model to define plasma output parameters for various input electrical energies and capillary radii of relevance to the electrothermal-chemical (ETC) propulsion concept. Three capillaries of 1.92, 4.75, and 7.0 mm radius, and a fixed length of 11.84 cm, were chosen for this study with input currents between 30 and 350 kA. Plasmas are categorized according to their total power and energy levels (based on a 3-ms pulse width) and are compared with respect to their resistance, exit pressure, and core plasma temperature. The input power ranges from 0.17 to 1.89 GW, for input energies from 0.49 to 5.80 MJ, which is considered suitable coverage for ETC ignition through ETC enhanced propulsion concepts. The study shows that the range of resistance, pressure, and temperature are 12.8–195 mΩ, 19.8–2000 MPa, and 2.9–13.5 eV, respectively, for the chosen capillary geometry. Flow conditions for plasma calculations include choked (no pressure boundary) and unchoked (450-MPa pressure boundary) for some calculations. Results from the computational model and interpretations from the perspective of capillary implementation into ETC propulsion concepts are also included.

Index Terms—Capillary, ionized gas, plasma, polyethylene, propulsion, pulsed power.

I. INTRODUCTION

HIGH energy plasmas are of interest to the electrothermal-chemical (ETC) propulsion concept where their use can potentially increase projectile kinetic energy, or it can provide a rapid and repeatable ignition source for conventional chemical combustion. A simplified diagram of the ETC concept is provided in Fig. 1, which includes illustrations of the plasma cartridge, working fluid, combustion chamber, pulse-forming network (PFN), and associated components of a typical ETC system. This paper emphasizes the characteristics of the plasma, which serves as an energy conversion mechanism between the PFN and combustion chamber for the ETC concept. Much research has been reported over the years in the areas of ETC propulsion and the physics relating to plasmas, which are characteristic of ETC systems [1]–[3].

This paper provides information from a recent study of ETC type plasma devices, in the form of theoretical calculations of plasma behavior under various operating conditions. The ETC plasma study includes the following conditions.

1) It analyzes and interprets plasma properties including steady state resistance, exit pressure, and core plasma temperature. Plasmas are assumed to be operating under freely expanding “choked flow” as well as “unchoked flow” conditions. The unchoked condition arises for some plasmas when a 450 MPa pressure boundary assumption is made.

2) Plasma calculations are performed for three capillary geometries having various radii and energy levels. Based on the results of the calculations, conclusions are drawn regarding the applicability of the different capillary dimensions for the various ETC propulsion concepts.

A. The Plasma Model

The plasma calculations undertaken here are performed with a quasi-steady state plasma model (Powell), which is discussed in more detail in other publications [4], [5] In the model, a potential difference applied between the anode and cathode of a hollow core capillary tube produces a current (I) that is conducted through a plasma arc in the interior of the cylindrical capillary. The current ohmically heats the plasma to temperatures of several tens of thousands of degrees. Radiation flux q from the heated plasma then ablates additional material from the capillary wall. This material replaces the plasma flowing out the open end of the capillary tube. A number of basic approximations and assumptions are made in the plasma model. First, the plasma is modeled using a one-dimensional (1-D) approximation. Such an approximation is probably valid at points in the capillary tube not too close to the tube wall. Near the wall, however, very steep gradients in the thermodynamic properties exist and the 1-D treatment is not valid. The procedure is to treat this region as a boundary of negligible thickness. Second, it is assumed that the problem can be treated in the steady state. Thus the flow variables do not change in time and the rate at which ablation occurs is identical to the rate of flow out the end of the tube. The cross-sectional area of the capillary is also assumed to be constant. Third, the effects of turbulent energy transfer are neglected. It has been argued that such effects are important because of the high Reynolds numbers associated with ETC plasmas, and some efforts to account for turbulence in a very approximated way have been undertaken [6]. The plasma is assumed to be a completely dissociated, homogeneous mixture of carbon and hydrogen atoms which originated from a polyethylene capillary. The ionization state in the capillary is calculated as a function of position down the tube, but it will be assumed that the plasma is at most doubly ionized. This assumption...
appears reasonable for typical temperatures and pressures. Electromagnetic ($J \times B$) forces are neglected. These forces can be expected to be negligible whenever the magnetic pressure is small compared to the hydrostatic pressure, a condition that is generally met for current magnitudes of interest. Resistive heating of the plasma is accounted for and cooling is assumed to occur through blackbody radiation.

From the law of partial pressures, the plasma pressure is given by

$$P = n_c(1 + x_{1c} + 2x_{2c})kT + n_{H}(1 + x_{1H})kT$$

(1)

or alternatively

$$P = \left[1 + x_{1c} + 2x_{2c} + \sigma(1 + x_{1H})kT\right] \rho = K\rho_s$$

(2)

Here $n_H$ and $n_C$ are the number densities of hydrogen and carbon heavy particles (atoms and ions); $x_{1c}$ and $x_{2c}$ represent the ratio of singly and doubly ionized carbon atoms to the total number of heavy carbon particles and $x_{1H}$ represents the corresponding ratio for hydrogen; $\sigma$ is the ratio of hydrogen to carbon particles (a constant); $m_{oc}$ and $m_{oH}$ are the atomic masses of carbon and hydrogen, respectively (also constants); $k$ is Boltzman’s constant, $T$ is the temperature, and $\rho$ is the plasma density. Electron and ion collisions are accounted for in calculating the electrical conductivity of the plasma which is given as

$$\sigma = \frac{n_e e^2}{m_e(\nu_{en} + \nu_{ei})}$$

(3)

in which $e$ is the electron charge, $n_e$ the electron concentration and $\nu_{en}$ and $\nu_{ei}$ are the collision frequency for neutrals and ions, respectively. From (3), the resistance of the plasma can now be found from the relation

$$R = \frac{l}{\sigma \pi \rho}$$

(4)

where $l$ is the plasma length, $\rho$ is the plasma radius, and $\pi$ is a constant. Finally, the expression for the plasma temperature is given as

$$T = \left(\frac{\sigma J^2}{2 \pi S}\right)^{1/4}$$

(5)

in which $J$ is the plasma current density and $S$ is Stefan’s constant.

### B. Plasma Model Assumptions

The plasma model is used here with the following additional assumptions. First, the liner material of the plasma capillary is considered to be polyethylene. Although other materials can be used for capillary liners (e.g., peek glass, polycarbonate, etc.), which may have varied properties such as heat of sublimation, polyethylene is considered a standard material whose behavior as a plasma generating device is similar, with respect to plasma power dissipation, conductivity, and temperature, to that of devices constructed from other materials [7]. In addition, the conductivity model implemented by the plasma model is that of Kurilenkov–Valuev [8]. The use of this model results in a modification to the Spitzer conductivity (3) by adjusting the collision frequency between electrons and ions ($\nu_{eq}$) at lower plasma temperatures. The plasma model has demonstrated good agreement with recent experimental plasma data [9]. Other plasma models have also been developed, which take into account these nonideal effects including that of Zollweg and Lieberman and Gunther and Radtke [10], [11]. The results from the plasma model used here compare within about 11% of the Zollweg–Lieberman model results over the energy and radii ranges considered in this paper. Finally, the calculated plasma temperatures are for the core or bulk plasma. The bulk temperatures predicted here take into account a plasma surface temperature assumption which is known to cause somewhat higher bulk plasma temperatures and conductivities with lower plasma exit pressures, compared to calculations performed that assume a completely isothermal case. In fact, the temperatures are between 14–37% higher for the calculations performed with the surface temperature assumption compared to the completely isothermal case. Also, although the plasma model itself is a 1-D model which solves for plasma parameters along the axis of the capillary, the model usage in the context of this paper is more of a zero-dimensional (0-D) analysis with the emphasis on a few selected plasma parameters at discrete plasma energy levels.

### C. Plasma Capillary Assumptions

For comparing plasma parameters such as resistance, pressure, and temperature, it was decided to examine the plasma behavior at equivalent plasma power and energy levels as opposed to electrical current level. This approach is desirable since two capillaries with different geometries, which are op-
erating at identical input current, can produce plasmas that exhibit widely differing powers and total energies. This is largely due to the inverse relationship between plasma resistance and capillary radius [see (4)] which produces different electrical power \((P)\) and energy regardless of identical current. Of course, because of the differences in capillary dimensions, the output parameters of interest (resistance, pressure, and temperature) will also exhibit great variation regardless of identical input current. As a result, it was decided to classify plasmas by power and energy level (based on an assumption of a 3 ms constant current input pulse) as opposed to the current level itself. An analysis can now be performed on plasmas (capillaries) having similar power and energy characteristics, which in general, are important criteria for determining the applicability to a given ETC concept.

For a given ETC design, however, a range of input electrical energies will be required for proper implementation, depending upon which ETC approach is selected. The source of this electrical energy is a high energy plasma. For example, for an ETC igniter, it is believed that less than 0.1 MJ of electrical energy over a period of several milliseconds will be required to properly ignite a 120-mm conventional propellant charge. This is based on simplified assumptions of energy content and discharge characteristics of standard benite primers presently used for ignition of large caliber (120-mm) propulsion systems [12]. On the other hand, for electrical enhancement of propellant burn rates or temperature compensation of conventional propellants, both of which could possibly result in enhanced propulsion performance, it is also believed that about 1 MJ of plasma energy will be required for proper ETC operation [3].

Three power levels as appropriate representatives of the requirements of the ETC concepts were selected for this study. These include approximately 180 MW, 700 MW, and 1.8 GW over a time constant of 3-ms pulse length, which produces three energy levels of approximately 500 kJ, 2 MJ, and 5 MJ. For the remainder of the paper, plasma properties will be plotted with respect to total plasma energy.

In addition, for the calculations performed here, the capillary lengths were fixed at 11.84 cm, which could realistically be used in a 120-mm caliber propulsion application. For simplicity, it was decided to investigate only three capillary radii selected for application to a 120-mm propulsion system: 1.92 mm, 4.75 mm, and 7.0 mm. For the remainder of the paper, the convention in referring to the capillaries will be as follows: capillary 1, 7.0-mm radius \(\times\) 11.84-cm length; capillary 2, 4.75-mm rad \(\times\) 11.84-cm length; and capillary 3, 1.92-mm rad \(\times\) 1.84-cm length.

In the following section, calculations are performed to determine the plasma resistance, pressure, and temperature of three different capillaries, at each power and energy level under consideration. The first set of calculations has no boundary pressure, while the latter are performed with a 450-MPa boundary pressure. The 450-MPa pressure boundary simulations are investigated since most ETC applications will require the injection of plasma into a pressurized combustion chamber having a peak chamber pressure as high as several hundred mega Pascals (MPa). The convention in referring to the nominal plasma energy level assumed in the calculations will be as follows: low, 0.5 MJ; medium, 2 MJ; and high energy level, 5 MJ.

II. RESULTS OF PLASMA CALCULATIONS

The steady-state resistance, exit pressure, and plasma core temperature were selected as parameters of interest and included in the investigation. For each of the capillaries (1–3), an input current was chosen to give the approximate power and energy level required by the study. The choice of input current is the result of a somewhat arbitrary process in which the plasma code is exercised in an iterative manner, until the input current and plasma resistance values are such that the plasma power and energy levels are close enough to the preselected values of power and energy. For this process, the plasma power is determined from the product of the calculated plasma voltage drop (dependent upon the conductivity characteristics of the plasma) and the test current at the given current level. Adjustments are made to the current, either additions or subtractions, until the projected power and energy levels are reasonably matched. For this study, agreement was obtained within about 18% of the projected values, although much better agreement could easily be obtained through further iteration with the code.
Fig. 4. Plasma energy versus core temperature for capillaries 1–3, with radii of 7.0, 4.75, and 1.92 mm, and choked flow condition.

Fig. 5. Plasma energy versus resistance for capillaries 2–3, with radii of 4.75 and 1.92 mm, showing the effect of the 450-MPa pressure boundary condition.

Since the plasma resistance plays a role in the transfer of electrical energy from a power supply to the plasma, the behavior of plasma resistance as a function of energy is investigated. For these calculations, unchoked flow is assumed by the model. The results are given in Fig. 2, for each of the three capillaries (1–3) at the given energy levels (low, medium, and high), where the plasma resistance varies from about 13 mΩ (capillary 1 at high energy) to as much as 195 mΩ (capillary 3 at low energy). Fig. 2 demonstrates rather strong relationships among plasma resistance, operating energy, and capillary radius.

It is noticed how a very large dynamic range results for capillary 3 (smallest diameter) resistance, over the given energy range, while the converse is true as the capillary radius is systematically increased. For capillary 1, plasma resistance varies between 12.8 and 30.5 mΩ over the entire range of energy, while for capillary 3, this change is wide from 54.9 to 195 mΩ.

Figs. 3 and 4 are plots of plasma energy versus plasma exit pressure and plasma temperature, respectively. The exit pressure is the pressure at the open end of the capillary where plasma gas initially appears as the plasma flows from the capillary, while the plasma temperature is that experienced in the core of the plasma. Once again, it is noted how capillary 3 has a wide (dynamic) range of exit pressures and core temperatures compared to capillaries 1 and 2.

Figs. 5–7 are the results of plasma calculations with the additional assumption of a pressure boundary condition at the plasma exiting plane. For this set of calculations, the boundary pressure is set at 450 MPa. For simplicity calculations are now performed only for capillaries 2 and 3 with all previous calculation assumptions remaining unchanged. The results for capillary 1, although not shown, do follow the same trends in the data that are given in the figures for the other capillaries. The results with the pressure boundary condition are plotted in Figs. 5–7 (broken lines) together with the results from the previous calculations, which did not have the externally applied 450-MPa pressure boundary (solid lines). Fig. 5 contains the plasma resistance relationships; Fig. 6 gives the exit pressure relationships; Fig. 7 shows the core temperature relationships.

III. DISCUSSION

For capillary 2, the exit pressure is obviously dominated by the boundary pressure of 450 MPa, with an increase of 406 (918%), 304 (208%), and 125 (39%) MPa for the low, medium, and high energies, respectively. The resulting temperatures are 5.2, 6.2, and 7.7 eV for the low, medium, and
high energy levels, respectively. This represents an increase in temperature of 1.63 (44%), 0.7 (13%), and 0.13 (1.3%) eV, compared to the previous calculations without the 450-MPa boundary condition. The resistance of the capillary 2 plasma is also sensitive to the pressure boundary, with a decrease in resistance ranging from 20.4 mΩ (39%) to 0.3 mΩ (1.5%) over the range of energies investigated.

General observations for capillaries 1 and 2 (larger diameters) include: 1) plasma output parameters of resistance, pressure, and temperature are less sensitive to the input energy level assumed in the calculations, compared to capillary 3 (smallest diameter); 2) pressure boundary conditions have a strong influence over all plasma parameters considered in the study, at nearly every energy level. Resistance tends to drop, exit pressure increases, and core temperature increases, for the plasmas of these capillaries, when the pressure boundary exists; and 3) lower exit pressures are experienced in nearly all calculations with these capillary dimensions (19.8–325 MPa). As a result, the ability for capillaries 1 and 2 to inject plasma into a pressurized combustion chamber remains in question at the relatively low plasma pressures calculated. Larger capillaries might therefore be best used purely as an ignition source where plasma injection late into the propulsion cycle is not a requirement and where plasma output parameters with respect to input energy level are more stable.

The relationships for capillary 3 are nearly unchanged by the added 450-MPa pressure boundary condition, regardless of energy level. In fact, for capillary 3, the plasma resistance is identical for medium and high energies, while it is only decreased by 11 mΩ (5.6% difference) for the low energy case. The pressure and temperature of the plasma from capillary 3 are increased by 215 MPa (91%) and 0.22 eV (3.8%), respectively, at low energy. The plasma remains completely unchanged in exit pressure and core temperature for medium and high energies. The output parameters of capillary 3 are obviously dominated by the self-generated capillary pressure at all energies considered, especially medium and high, regardless of the 450-MPa pressure boundary condition. Based on these results, it seems reasonable that such a capillary would be appropriate for ETC propulsion concepts requiring continued plasma flow from the capillary into the combustion chamber, during the projected propulsion cycle.

The summary of observations for capillary 3 (small diameter) calculations includes the following.

1) Exit pressures and core temperatures increase more rapidly with increased input energy, compared to the other capillaries examined. The plasma resistance decreases more rapidly as input energy is increased.

2) The small diameter capillary is much less sensitive to pressure boundary conditions at the exit plane of the capillary, with respect to resistance, exit pressure, and core temperature, in comparison with other capillaries in the study. In fact, in some calculations, the output is completely unchanged by the pressure boundary, which indicates the kinetic pressure of the plasma is dominant.

3) Exit pressures and core temperatures achieved extreme levels (2000 MPa, 13.5 eV) as the energy approached 5 MJ.

In summarizing this set of calculations, capillaries having diameters similar to those of capillary 3 appear to be best for plasma injection into a pressurized combustion chamber, perhaps late into the propulsion cycle. Of course, this may come at the expense of a very high core temperature and a somewhat higher plasma resistance and pressure. The use of smaller (diameter) capillaries for ETC performance augmentation will then require the ability to employ higher temperature plasmas as well as make use of pulsed power supplies of higher impedances, although the latter of these should not be difficult. In addition, the ability to utilize plasmas with widely fluctuating output parameters must be considered, if a variety of energy levels are needed for proper ETC operation. This is attributable to the large dynamic range observed for each of the plasma output parameters (resistance, pressure, temperature) as a function of input energy.

Additional calculations were performed for the purpose of further understanding the behavior of plasma parameters (resistance, exit pressure, and core temperature) as a function of total plasma energy. Of specific interest is the greater dependence of resistance, pressure, and temperature on the plasma energy for the small capillary (capillary 3) compared to the larger capillaries (capillaries 1 and 2). By examination of the conductivity relation (3), it is clear that the plasma conductivity is directly proportional to the electron concentration ($n_e$) and inversely proportional to the electron-neutral ($\nu_{en}$) and electron-ion ($\nu_{ei}$) collision frequencies. Although the conductivity is a function of both $\nu_{en}$ and $\nu_{ei}$, for all the calculations considered in this paper, $\nu_{ei}$ is the dominant term of the two. For example, for capillary 1 over the range of energy examined (“low” to “high”), $\nu_{en}$ is between 2 × 10¹¹ and 6 × 10¹¹, which are about two orders of magnitude less than the values of $\nu_{ei}$ for the same energy range. For the case of a large capillary (e.g., capillary 1) as the plasma energy is varied from low to high, the electron concentration ($n_e$) increases from 2 × 10²⁶ m⁻³ to 8.3 × 10²⁵ m⁻³ while the $\nu_{ei}$ increases from 2.2 × 10¹² to 3.9 × 10¹³. The resultant plasma conductivity is increased by a factor of 2.3, which is illustrated in the plasma resistance plot of Fig. 2. In similar conductivity calculations for the small radius capillary (capillary 3) the electron concentration increases from 1.52 × 10²⁶ to 5.3 × 10²⁶ over the energy range, but now the electron-ion collision frequency is nearly constant and actually decreases from 8 × 10¹³ to 7.9 × 10¹³. The net result is a larger increase in plasma conductivity (a factor of 3.5) for the small capillary compared to the larger capillary. The larger capillary conductivity exhibits a reduced sensitivity to plasma energy compared to the smaller capillary due to the combined effect of electron concentration and electron-ion collision frequency, which have opposite effects on conductivity as plasma energy is increased. For the smaller capillary, the conductivity is a stronger function of plasma energy since it is more dependent upon the electron concentration and not on electron-ion collision frequency which is nearly constant at higher plasma energy.

The plasma temperature is given by (5) which is dependent upon the plasma current density and conductivity. However, the plasma temperature, through its dependence upon current
density which is indirectly proportional to the capillary radius squared, is indirectly proportional to the capillary radius to the 0.75 power [see (5)]. The temperature is also directly proportional to the conductivity to the 0.25 power. As a result, the plasma temperature exhibits a stronger relationship with input current and plasma energy for small radius capillaries and a weaker functional relationship with larger radius capillaries as indicated by the results of Fig. 4.

The plasma kinetic pressure is determined from (1) and (2) and from (2), pressure is shown to be directly proportional to the plasma density, \( \rho \), and the \( K \) term, which is a function of ionization ratio, heavy particle ratio, and plasma temperature. Calculations based upon these relations for capillary 1 demonstrate that the low energy level value of \( K \) is \( 1.14 \times 10^8 \) while \( \rho \) is 0.174, which when multiplied together, give a kinetic pressure of 19.8 MPa. The high energy values of \( K \) and \( \rho \) are \( 2.85 \times 10^8 \) and 0.508, respectively, which result in kinetic pressure of 235 MPa, as indicated by the plot in Fig. 3. Capillary 3 values of \( K \) and \( \rho \) are \( 2.29 \times 10^8 \) and 1.02, respectively, giving a kinetic pressure of 233 MPa at low energy, and \( 6.43 \times 10^8 \) and 3.17, respectively, giving a kinetic pressure of more than 2 GPa at the high energy level. This relationship is also illustrated in the plot of Fig. 3. Due to the stronger relationships of plasma temperature and density as functions of energy, the resulting capillary pressure is also a stronger function of plasma energy for the smaller capillary.

The large dynamic range observed in capillary 3 may have practical limitations if relied upon in an ETC application. For example, it has been shown in previous investigations that the electrical transfer efficiency of a fixed impedance pulsed power supply will exhibit a poor (approximately 40%) electrical transfer efficiency for capillaries having a resistance unmatched to that of the power supply [13]. As a result, one might expect that a fixed impedance power supply will have a large variation in transfer efficiency with small diameter capillaries, over a given range of input power and energy levels. Large capillary plasmas could therefore be described as more stable in terms of their impedance behavior and transfer efficiencies with respect to power and energy input levels. One technical method of overcoming variations in transfer efficiency is to allow the impedance of the power supply to fluctuate with the plasma resistance. This, of course, could translate into a more complex power supply in terms of additional switching and control components that are necessary to achieve a more dynamic power supply.

Additional computations and experiments for the purpose of further defining the behavior of plasmas at energy levels and of dimensions appropriate for ETC applications should be pursued before drawing final conclusions with regard to optimal ETC plasma capillaries. The calculations contained within this paper are taken with what could be considered as potentially limiting assumptions (e.g., one-dimensionality, isothermal plasma, exclusion of hydrodynamics effects). As a result, it is recommended to continue theoretical and experimental investigations with increasing levels of complexity (e.g., nonisothermal plasma conditions and 1-D and two-dimensional (2-D) time-dependent models) before any serious or profound conclusions are made with regard to ETC plasma capillary selection.

IV. SUMMARY AND CONCLUSIONS

Theoretical calculations have been performed with a steady state, isothermal plasma model with the objective of defining high energy plasma output parameters of interest to the ETC propulsion concept. Capillary radii of 1.92, 4.75, and 7.00 mm were chosen and the input current level was varied between 30 kA and 350 kA for capillaries having a fixed length of 11.84 cm. The range of plasma powers and energies investigated include 0.17–1.89 GW and 0.49–5.80 MJ, respectively. The plasma output parameters (resistance, exit pressure, and core temperature) fluctuated greatly over the range of energy and chosen capillary diameter. The range of resistance, pressure, and temperature are 12.8–195 \( \text{m}^\Omega \), 19.8–2000 MPa, and 2.9–13.5 eV, respectively. The effect of a 450-MPa external pressure boundary condition was noticed to have a more significant impact on the plasma output parameters for large diameter capillaries and little or no impact on small diameter capillaries.

Large diameter capillaries studied here (capillaries 1 and 2) showed a reduced sensitivity to the plasma energy level with respect to output parameters (resistance, pressure, temperature), an externally applied pressure boundary condition (450 MPa) had a strong influence on plasma output parameters, and the self-generated plasma kinetic pressures were, in general, much less than those of the small capillary (capillary 3). Based on these observations, it appeared that a larger capillary might best be used in the application of an ETC igniter.

The small diameter capillary (3) was observed to have output parameters that were much more sensitive to the plasma energy level used; it was much less sensitive to the externally applied (450 MPa) pressure boundary condition, and it produced very large exit pressures and core temperatures. As a result, it might appear that a smaller diameter capillary would be best for applications where injection of plasma into a combustion chamber for a longer period into the propulsion cycle, such as ETC performance augmentation, is a requirement.

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