

Radiation Heat Transfer and Vapor Shielding in a Two-Dimensional Model of an Electrothermal Plasma Source

Micah Esmond¹  · Leigh Winfrey²

Published online: 28 March 2016
© Springer Science+Business Media New York 2016

Abstract Electrothermal (ET) plasma discharges are emerging as valuable mechanisms for pellet injection in magnetic confinement fusion reactors. They have been shown to be capable of achieving the required pellet velocities and pellet launch frequencies required for edge localized mode control. Another advantage of ET plasma discharges is their ability to simulate fusion disruption events by depositing large heat fluxes on exposed materials. A deeper understanding of the heat transfer processes occurring in ET plasma discharges will aid in this particular application. ET plasma discharges involve the passage of high currents (order of tens of kA) along the axis of a narrow, cylindrical channel. As the current passes through the channel, radiant heat is transferred from the plasma core to the capillary wall. Ablated particles eventually fill the plasma channel and the partially ionized plasma is ejected. It is well known that the ablated material separating the plasma core from the ablating surface can act as a vapor shield and limit the radiation heat flux reaching the ablating surface. In this work, the results from a two-dimensional simulation model for ET plasma discharges are presented. The simulation of the plasma in a two-dimensional domain combined with the diffusion approximation

for radiation heat transfer is shown to successfully simulate the effects of the vapor shield layer that develops inside these devices.

Keywords High heat flux sources · Vapor shielding · Electrothermal plasma

Introduction

Electrothermal (ET) plasma discharges are characterized by rapid heating and the resulting surface ablation inside a capillary geometry. Relatively large currents (tens of kA) initiate ionization and joule heating inside these devices. A schematic of an ET plasma source is shown in Fig. 1. Heat is transferred from the plasma to the ablating surface primarily through radiation [31]. Ablated particles fill the capillary and are ejected out the open end as a plasma jet. Ablated particles can form a dense cloud of vapor separating the plasma core from the ablating surface. This vapor layer can block incoming radiation from the plasma core and prevent it from reaching the ablating surface. This effect is known as vapor shielding [11].

ET plasma discharges are being studied for their application to electric propulsion [23, 24] and solid propellant ignition [6, 18, 25, 27]. These devices are also being explored for their potential use in pellet launcher systems for magnetic confinement fusion reactors [16, 28, 30]. ET plasma launchers offer several engineering advantages including a simple design, wide pellet exit velocity range, and the capability of firing pellets at frequencies suitable for ELM control [9]. In addition, ET plasma discharges are being used to deliver high heat fluxes expected during disruption events in future fusion reactors [4, 10]. The investigation of the use of ET plasma discharges as

✉ Micah Esmond
mesmond@vt.edu

Leigh Winfrey
winfrey@mse.ufl.edu

¹ Nuclear Engineering Program, Department of Mechanical Engineering, Virginia Polytechnic Institute and State University, Blacksburg, VA 24061-0238, USA

² Nuclear Engineering Program, Department of Materials Science and Engineering, University of Florida, Gainesville, FL 32611-6400, USA

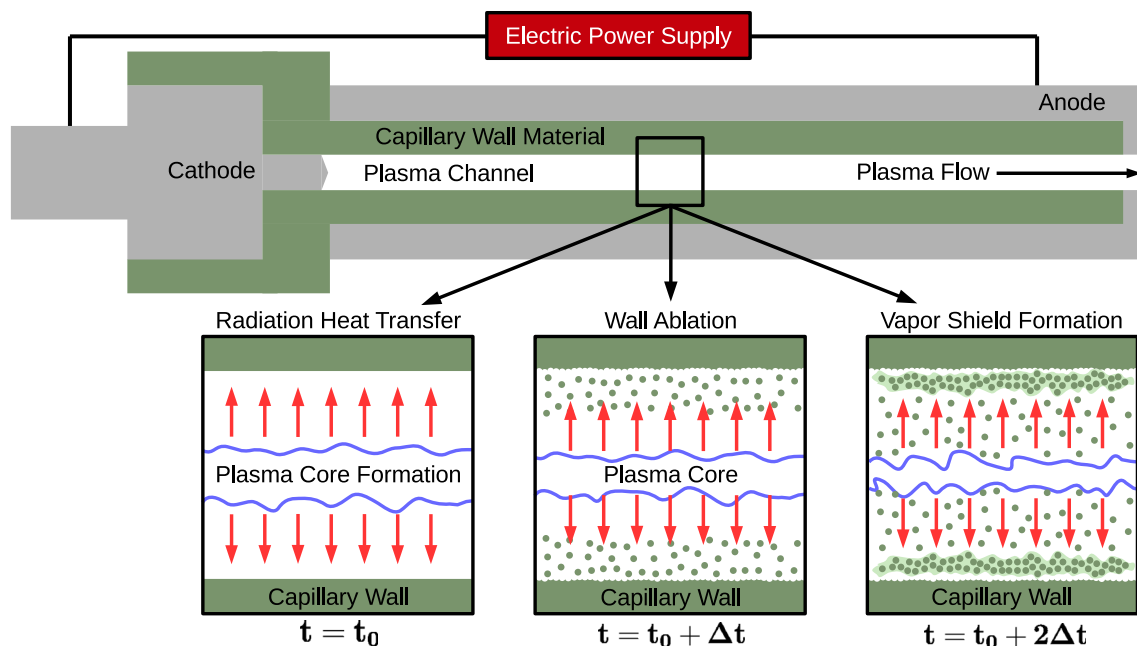


Fig. 1 A schematic of an ET plasma source. Electric current flows through the plasma channel from the cathode to the anode. Heat is radiated from the plasma core to the capillary wall, and ablation is induced. Dense clouds of ablated vapor can build up and separate the

plasma core from the capillary wall. This effect gives rise to vapor shielding. ET plasma source geometries are typically cm in length and mm in internal diameter

high heat flux sources has been accompanied by simulation results [5]. To provide better support for these studies and deeper insight into the relationship between ablation and surface heat flux, improvements in the simulation and modeling capabilities for ET plasma discharges are required.

The ablation inside an ET plasma discharge is known to form a vapor layer separating the source liner from the plasma core. This vapor layer shields the ablating surface and limits the heat flux from the plasma core to the ablating surface [2, 11]. The boundary layer that forms between the plasma core and the ablating surface has been studied in detail by Eapen [3] and Orton [22]. These studies reinforced the concept of the vapor shield layer. Eapen and Orton focused on 2D simulation of plasma flow over a flat plate. Consequently, their results were not directly comparable with ET plasma discharge experiments. Eapen [3] expressed the need for a fully 2D model of an ET plasma source in order to sufficiently capture the fundamental physics near the ablating surface.

Foundational theoretical and semi-empirical studies were performed by Niemeyer [21] and Ibrahim [15]. Kovitya and Lowke [17] later developed a 1D, steady-state model in order to further explore the details of ET plasma discharges. They used different approximations for the radiation heat transfer from the plasma, and their results suggested that a black-body radiation approximation was well-suited to discharges with discharge current greater

than 4 kA. Ruchti and Niemeyer [26] developed theoretical scaling laws for ET plasma discharge devices (a.k.a. ablation controlled arcs). These authors focused on the determination of a transparency factor which accounted for the vapor shield layer. Time-dependent modeling of pulsed ET discharge devices was performed by Gilligan and Mohanti [12] with a 0D model. These authors compared their simulation results for steady-state discharge operation with the work of Ruchti and Niemeyer [26]. Gilligan and Mohanti also compared their simulation results with pulsed ET discharge experiments that were being performed by Bourham et al. [2]. Gilligan and Mohanti [12] utilized a vapor shield factor defined as the ratio of the radiation flux reaching the ablating surface to the black-body radiation flux coming from the plasma. They adjusted the vapor shield factor in order to align simulation results with experiment. They estimated the vapor shield factor to be approximately 10 %.

In the 1990s, simulation and modeling capabilities for pulsed ET plasma discharge devices progressed to 1D [14]. Hurley et al. [14] used an adaptive vapor shield factor which depended on the plasma pressure, internal energy, and sublimation energy of the liner material. However, this adaptive form for the vapor shield factor was later contested by Zaghoul et al. in favor of a constant value for the vapor shield factor [32]. Zaghoul suggested that the constant vapor shield factor be tuned in order to match simulation predictions with experimental results.

The 1D modeling capabilities were later advanced to semi-2D by Ngo et al. [20]. The semi-2D model relied on a 1D solution of bulk plasma properties and then estimated radial gradients using an radial energy equation. However, the 1D solution relied on a volumetric source term for the ablated material rather than treating the ablation as a surface flux. This limits the ability of this semi-2D model to capture important details at the ablating surface.

More recent studies have focused on a grey-body treatment of the plasma inside ET plasma discharges. Zaghoul [31] and Pekker et al. [24] used different methods in determining the emissivity of the plasma. Zaghoul performed calculations using a 1D model, and Pekker used a 0D model. These models still incorporate ablation as a volumetric source term, which prevents the ability to capture effects occurring close to the ablating surface.

In order to address the need for a fully-2D simulation model and code for pulsed ET plasma discharge devices, the Three-fluid, 2D ET Plasma Flow Simulator (THOR) model and code have been developed. THOR couples the 2D hydrodynamics with the heat transfer effects occurring inside ET plasma devices during discharge and provides a unique and novel method of investigating the fundamental physics occurring inside these devices. The THOR simulation code is equipped to use two different approximations for the radiation heat transfer. The first approximation is a black-body approximation, and the second, a diffusion approximation. In this work, the model equations for the different radiation approximations are discussed. Simulation results are compared with experiment, and key differences between the black-body and diffusion approximations are highlighted. Lastly, the vapor shield layer simulated using the diffusion approximation for radiation heat transfer is illustrated and discussed.

Model Formulation

The THOR model and code simulate the evolution and interaction of the electron, ion, and neutral species inside ET plasma discharges in a 2D, axisymmetric domain. The electrons are simulated using the drift-diffusion approximation. The ions and neutrals are simulated using the Euler gas-dynamic equations. A first approximation for the electric field using Ohm's law is also implemented. The governing equations used in the THOR model have been introduced previously by Esmond and Winfrey [8]. Based on their work, charge exchange effects are not expected to alter results presented here by more than a few percent. Therefore, charge exchange effects have been neglected for the simulations reported in this work. In this section, the approximations used in the THOR code for radiation heat transfer are discussed in detail.

Radiation: Black-Body Approximation

The THOR code can utilize a black-body radiation approximation for determining the radiation heat flux from the plasma to the ablating surface. For this approximation, an average temperature is determined for the heavy species over the geometric cross section of the source. The black-body radiation coming from the plasma, q''_{rad} , is then evaluated based on this average temperature.

$$q''_{rad} = \sigma(T_{avg}^4 - T_{boil}^4) \quad (1)$$

where σ is the Stefan–Boltzmann constant, T_{avg} is the averaged heavy particle temperature, and T_{boil} is the boiling temperature of the source liner material. Previous 0D and 1D models have utilized a vapor shield factor that allows only a fraction of the black body radiation to reach the ablating surface. In these models, the vapor shield factor is typically tuned to match simulation results with experiment [1, 12, 32]. This approach has been avoided in the present model, and no correction factor has been used to adjust the radiation flux.

In the THOR code, the black-body radiation heat flux in Eq. (1) is deposited on the ablating surface and all the energy is assumed to go into causing ablation. Investigations of the effects of incorporating absorption of the radiation heat flux into the wall material have been performed for similar devices [24]. The inclusion of heat flux absorption by the wall material is not expected to significantly alter the results presented in this work, and the inclusion of these effects in the present model has been put off to a later date.

Radiation: Diffusion Approximation

It has been shown that the diffusion approximation for radiation heat transfer is valid for the plasmas that develop inside ET plasma discharges provided that a radiation flux limiter is used [13]. Careful attention must also be paid to the radiation flux boundary condition at the ablating surface in these devices. A radiation flux boundary condition and flux limiter have been established through the work of Hahn and Gilligan [13]. These authors used a radiation flux boundary condition at the ablating surface given by

$$S_g = \frac{c}{2} U_g \quad (2)$$

where S_g is the boundary radiation flux for frequency group g , c is the speed of light, and U_g is the radiant energy. This boundary condition is suggested due to the strong anisotropy of the radiation field at the interface between the ablating surface and the plasma. These authors argue for this condition based on the similarity between the ablating surface boundary and a vacuum-fluid boundary [13]. Hahn

and Gilligan also establish the radiation flux limit to be equal to the radiation flux specified in Eq. (2).

The diffusion model for radiation heat transfer used in THOR incorporates the findings of Hahn and Gilligan and also uses the approach adopted by Ngo [20]. It should be noted that Hahn and Gilligan utilized a multi-group diffusion model. In this work, to limit the complexity of the problem, an averaged-group diffusion model has been used. A similar approach was used by Ngo. Therefore, the boundary condition and flux limit for radiation heat transfer are given by

$$S_{rad} = \frac{c}{2} U_p \quad (3)$$

where $U_p = 4\sigma T_p^4/c$ is the radiant energy of the plasma, and T_p is the plasma temperature. The plasma temperature at the boundary of the domain is used to determine the boundary radiation flux per Eq. (3).

By the diffusion approximation, the radiation heat flux within the simulation domain is given by

$$\mathbf{q}_{rad} = -k_{rad} \nabla T_p \quad (4)$$

where k_{rad} is the radiation thermal conductivity. The radiation thermal conductivity is given by [20, 33]

$$k_{rad} = \frac{16}{3} \sigma l_{rad} T_p^3 \quad (5)$$

where l_{rad} is the radiation mean free path. The radiation mean free path is approximated by [33]

$$l_{rad} = 0.9017 \frac{m_e^{3/2} c}{h^2 k_e^3 e^6 N^2 \bar{Z} (\bar{Z} + 1)^2} \text{ meters} \quad (6)$$

where m_e is the electron mass in (kg), c is the speed of light in (m/s), h is Planck's constant in (J s), k_e is the Coulomb constant in (Nm^2/C^2), e is the electron charge in (C), k_B is Boltzmann's constant in (J/K), T_p is the plasma temperature in (K), N is the total number density in (m^{-3}), and \bar{Z} is the average charge state (unitless). It should be noted that the form used by Zeldovich and Raizer for the radiation mean free path is in CGS units [33]. This form has been converted to MKS units in Eq. (6). In the present work, the radiation energy transferred in the domain is distributed between the ion and neutral species based on their mole fractions.

Ablation

The ablation at the surface of the source liner is determined based on the radiation flux to the surface and the heat of sublimation of the source liner material [12, 14, 29, 32].

$$\phi_{abl} = \frac{q''_{rad}}{H_{sub}} \quad (7)$$

where ϕ_{abl} is the ablating particle flux at the ablating surface [$1/(\text{m}^2\text{s})$], q''_{rad} is the radiation heat flux to the ablating surface (W/m^2), and H_{sub} is the heat of sublimation per particle of the ablating surface material (J).

Results and Discussion

The computational investigations reported in this work were of an ET plasma source with a 9 cm length and a 2 mm radius. The source liner material used in this study was Lexan polycarbonate, or $(\text{C}_{16}\text{H}_{14}\text{O}_3)_n$. The sublimation energy for Lexan polycarbonate has been approximated to be 54 MJ/kg [19]. The average particle mass is 1.28×10^{-26} kg, and therefore, in this work, $H_{sub} = 6.91 \times 10^{-19}$ J/particle. Experimental measurements reported in this work were performed by Winfrey et al. [29]. The THOR simulation code was used to acquire simulation results for both the black-body radiation approximation and the diffusion approximation for radiation heat transfer. The black-body radiation results reported in this work were obtained using a computational mesh with $\Delta z = 2.14 \times 10^{-4}$ m and $\Delta r = 7.14 \times 10^{-5}$ m. The diffusion approximation results were obtained using a computational mesh of $\Delta z = 2.5 \times 10^{-4}$ m and $\Delta r = 5.56 \times 10^{-5}$ m. Experimentally measured current pulses are used as simulation inputs. Experiments have been performed using the Plasma Interaction with Propellant Experiment (PIPE) and reported in the work of Winfrey et al. [29]. Simulation results from four PIPE shots are reported in this work. The four PIPE shots are identified as P213, P215, P228, and P204. These PIPE shots have nominal peak currents of 10, 20, 30, and 40 kA, and input shot energies of 1.09, 2.42, 4.09, and 5.91 kJ, respectively. Each current pulse has an active pulse length of approximately 100 μs . Current pulses for these shots are well-documented [29].

Validation of the THOR model and code has been performed by comparing the total predicted ablated mass with the total measured ablated mass. This comparison is shown in Fig. 2. Figure 2 indicates that the results from the black-body radiation approximation align better with experiment at input shot energies less than 3 kJ. However, the black-body radiation approximation tends to overestimate the total ablated mass at input shot energies higher than 3 kJ. The diffusion approximation for radiation heat transfer underestimates the total ablated mass for input shot energies less than 3 kJ, but predicts ablated mass values within the experimental uncertainty for input shot energies higher than 3 kJ. This difference in the lower (i.e. <3 kJ) and higher (i.e. >3 kJ) input shot energies has been observed

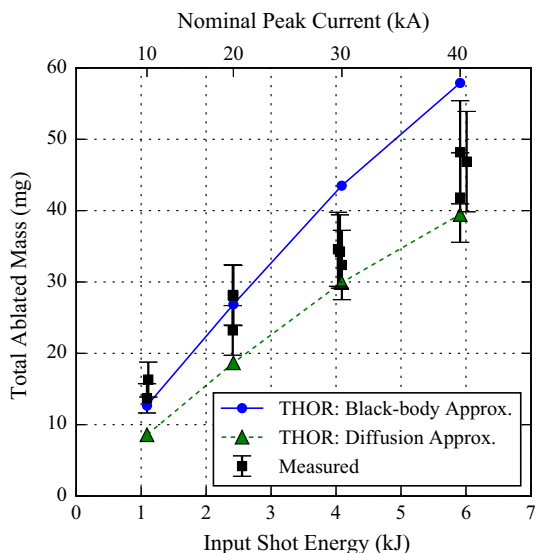


Fig. 2 The total ablated mass predicted using the THOR simulation code is compared with experimentally measured ablated mass. Experimental measurements are reported by Winfrey et al. [29]. Four different current pulses, P213, P215, P228, and P204, were simulated using the THOR simulation code with both the black-body and diffusion approximations for radiation heat transfer. THOR simulations were run to a simulation time of 250 μ s

by Winfrey et al. [29]. These authors focused on ideal versus non-ideal behavior of the plasma. Their findings suggest that plasma non-ideality becomes more important as the discharge energy increases. Similarly, in this work, the results indicate that detailed estimation of the radiation heat flux becomes more important as the discharge energy increases. This observation is consistent with the work of AlMousa [1] who observed that the vapor shield layer becomes more important at higher discharge energies. The vapor shield layer develops as ablated particles enter the capillary source and shield the capillary walls from incoming plasma radiation. In the THOR code, the diffusion approximation for radiation heat transfer accounts for this vapor shield layer by forcing thermal energy to diffuse from the plasma core through the ablated vapor toward the ablating surface. This technique of capturing the effects of the vapor shield layer has not been implemented previously. The black-body approximation ignores the vapor shield layer and allows energy to be transferred directly from the plasma core to the ablating surface. This results in an overestimation of total ablated mass at input discharge energies > 3 kJ.

Each of the four PIPE current shots were simulated with both the black-body and diffusion approximations for radiation heat transfer. Therefore, a total of eight simulations are represented in this work. The ablation rates predicted in each simulation are shown as a function of simulation time in Fig. 3. As implied in Fig. 2, the

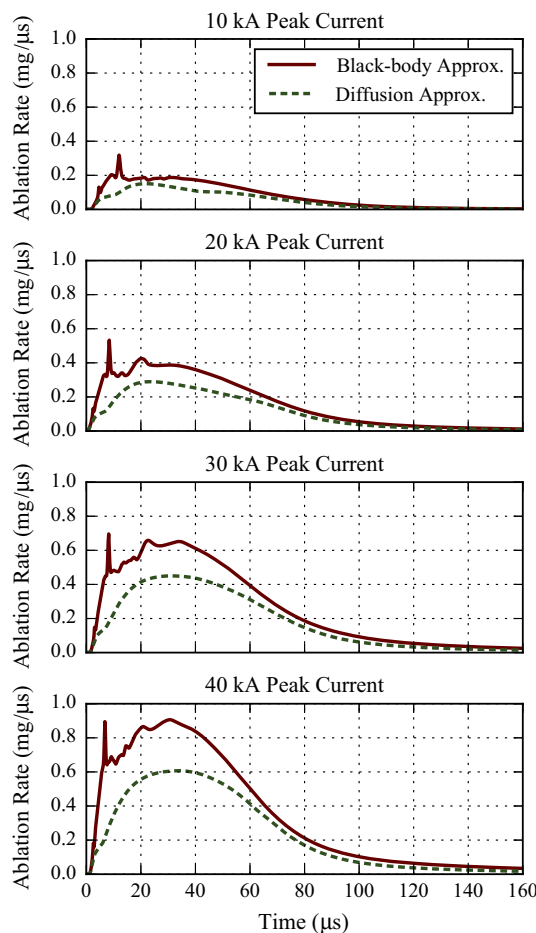


Fig. 3 The ablation rate time history for each of the eight THOR simulations represented in this work

diffusion approximation for radiation heat transfer results in a lower ablation rate throughout the simulation. As discussed later, this lower ablation rate is due primarily to the ability of the diffusion approximation to capture the effects of the vapor shield layer which reduces ablation. The black-body radiation approximation predicts relatively high transience in the ablation rate early in the discharge as shown in Fig. 3. This transience has been investigated in more detail in a previous work [7]. In contrast to the black-body results, the diffusion approximation results show a relatively steady rise and fall in the ablation rate as the input current increases and recedes.

To further investigate the differences in the two approximations for radiation heat transfer, the time evolution of the radial distribution of the neutral temperature is shown in Fig. 4. The neutral temperature is representative of the plasma temperature as the species tend toward local thermodynamic equilibrium. The black-body radiation approximation predicts a very fast rise in temperature at the core of the ET plasma source. This happens during the first 10 μ s of the discharge. As the simulation progresses, the

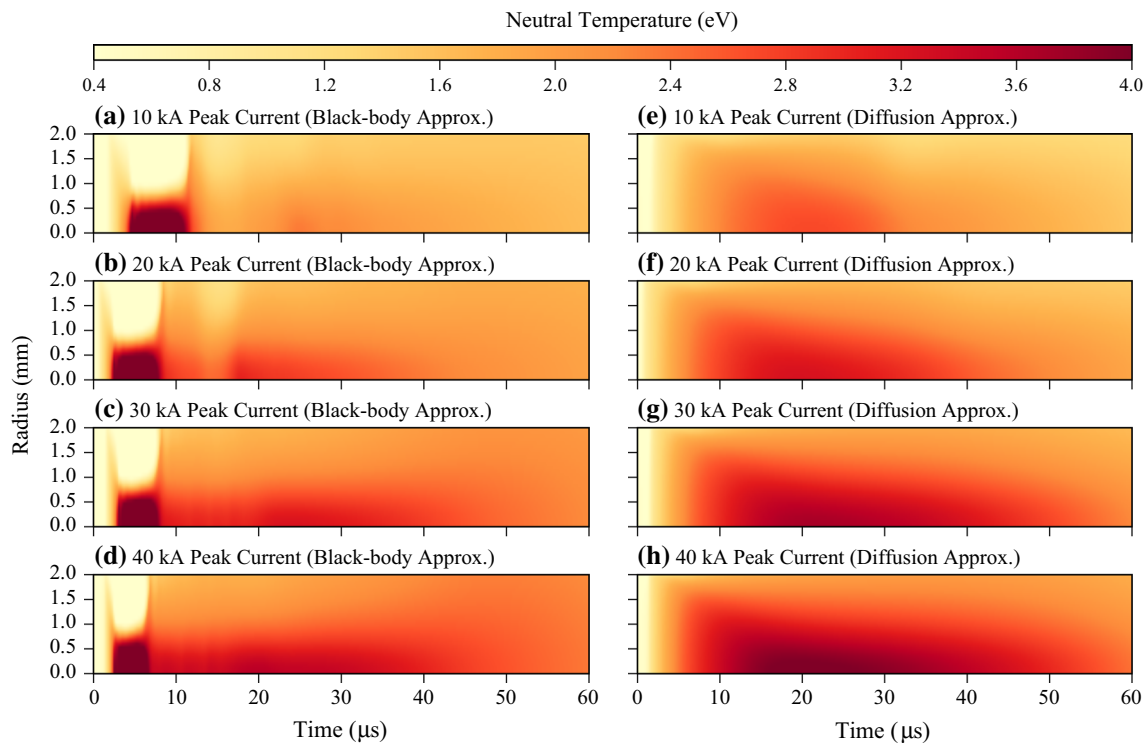


Fig. 4 The time history of the neutral species temperature distribution over the midpoint of the source (i.e. $z = 4.5$ cm). Black-body radiation results are shown in **a–d**, diffusion approximation results are shown in **e–h**

core temperature quickly diminishes as the temperature over the remainder of the source cross-section rises. It is interesting to note the similarity between the results shown in Fig. 4a–d and the results presented by Zaghoul [31]. Zaghoul performed a simulation of a 40 kA peak current shot and focused on reproducing the experimental ohmic power input to the source. Zaghoul observed a spike in the plasma temperature at the beginning of the discharge similar to those observed in Fig. 4. In this work, and in that of Zaghoul, the initial spike in the temperature is attributable to the lower initial plasma density. At lower plasma densities, the high ohmic power input from the electric current will quickly raise the temperature of the plasma. As the plasma density increases due to ablation, the plasma temperature reduces. The diffusion approximation for radiation heat transfer predicts a relatively gradual rise in the temperature over the cross section of the source. This is due to rapid diffusion of thermal energy by radiation heat transfer. Radiation diffusion is more rapid at the beginning of the simulation due to the lower initial plasma densities.

After discharge initialization (approx. $12 \mu\text{s}$), the radial temperature gradients observed for the diffusion approximation are greater than those predicted in the black-body approximation. This is due to the direct energy transfer from the plasma core to the ablating surface via the black-

body radiation approximation. By using the diffusion approximation, this energy at the plasma core must diffuse through the plasma bulk in order to reach the ablating surface. This effect increases temperature gradients in the radial direction inside the ET plasma source. In Fig. 5, the temperature distributions at the source midpoint ($z = 4.5\text{cm}$) of the ET plasma source at simulation times of $30 \mu\text{s}$ are shown for each simulation. The higher temperatures at the plasma core predicted by the diffusion approximation result in a higher electrical conductivity. Higher electrical conductivity reduces the ohmic power deposited in the device. The lowered energy deposition plays a role in lowering the total predicted ablated mass for these simulations (see Fig. 2).

Further investigation of the simulation results reveals information about the development of the vapor shield layer separating the plasma core from the ablating surface. As discussed earlier, the diffusion approximation for radiation heat transfer relies on the radiation thermal conductivity k_{rad} . The radiation thermal conductivity can be used as an indicator of the vapor shield layer inside the ET plasma source during operation. The full spacial distribution of the radiation thermal conductivity inside the ET plasma source is shown for each simulation at a simulation time of $30 \mu\text{s}$ in Fig. 6. For the black-body radiation approximation, there is little evidence of a vapor layer

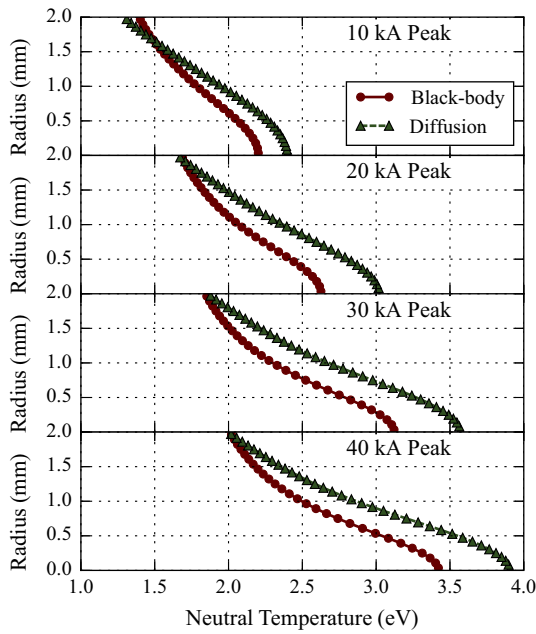


Fig. 5 Neutral species radial temperature distribution at the source midpoint ($z = 4.5$ cm) at a simulation time of $30 \mu\text{s}$

forming at the boundary between the plasma core and the ablating surface (see Fig. 6a–d). It should be noted that the black-body radiation approximation results do not

incorporate the use of the radiation thermal conductivity; it is shown here for comparison. The diffusion approximation results clearly indicate the development of a vapor shield layer which is indicated by the region of relatively low radiation thermal conductivity near the ablating surface (see Fig. 6e–h). The radiation thermal conductivity is lower near the ablating surface because of generally lower temperatures and increased particle density due to ablation. This lower radiation thermal conductivity is indicative of the vapor shield layer which limits the heat transfer from the plasma core to the ablating surface. The dashed line shown in Fig. 6a–h indicates the estimated thickness of the vapor shield layer [15].

The distributions of the radiation thermal conductivity for the diffusion approximation results are shown at the source midpoint in Fig. 7. The radiation thermal conductivity is higher for the 10 kA peak current shot due to the lower particle densities caused by less ablation. Higher ablation, as in the cases of the 20, 30, and 40 kA peak current pulses, leads to a lower radiation thermal conductivity overall. Figure 7 highlights the vapor shield layer and shows that in this layer, the radiation thermal conductivity is less than or equal to 4 % of the maximum radiation thermal conductivity of the same current shot at simulation times of peak discharge current. The thickness of the vapor

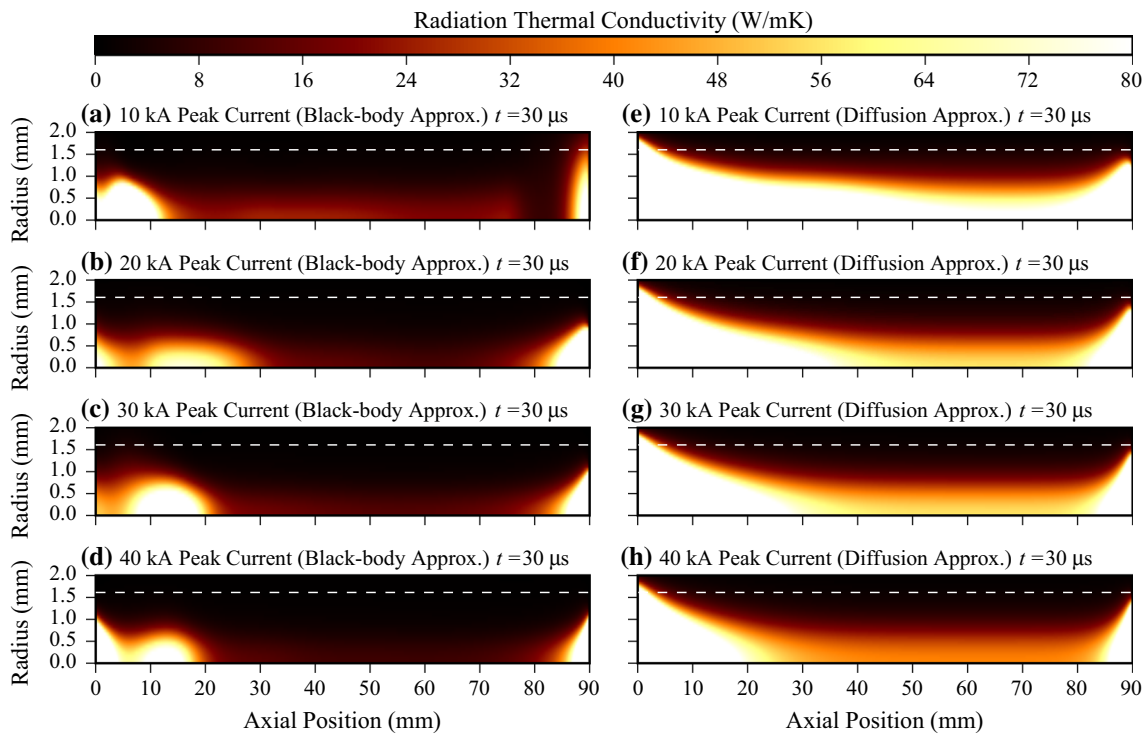


Fig. 6 Full distributions of the radiation thermal conductivity. Black-body approximation results are shown in a–d, and diffusion approximation results are shown in e–h. The simulation time for each distribution is $30 \mu\text{s}$ corresponding roughly to the time of peak current. The ablating surface is at a radius of 2 mm. The source

centerline is at a radius of 0 mm. The dashed line in each plot indicates the thickness of the vapor shield layer as estimated by Ibrahim [15]. The radiation thermal conductivity is not incorporated in the black-body radiation model but is shown in a–d for the sake of comparison

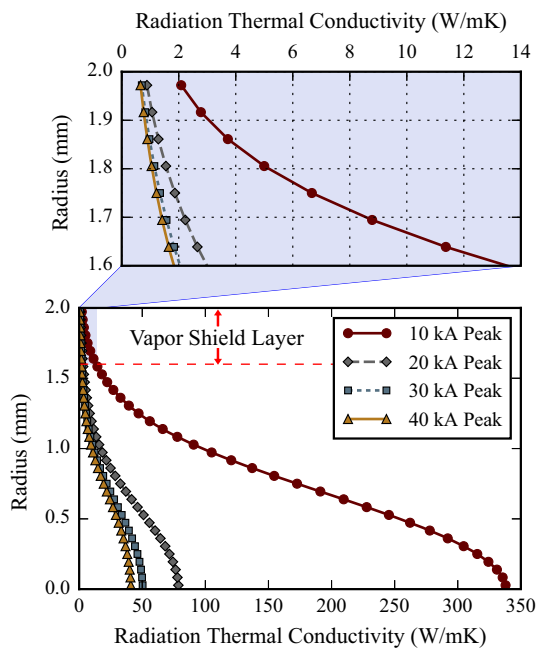


Fig. 7 The radial distribution of the radiation thermal conductivity for the 10, 20, 30, and 40 kA peak current pulse simulations using the diffusion approximation for radiation heat transfer. The dashed line indicates approximate thickness of the vapor shield layer as estimated by Ibrahim [15]. Results are shown for simulation times corresponding to the time of peak current in each discharge

shield layer shown in Fig. 7 is based on an estimate made by Ibrahim [15].

Conclusions

The Three-fluid, 2D ET Plasma Flow Simulator (THOR) has been developed in order to investigate the fundamental physics occurring inside ET plasma discharges in more detail than previously possible. THOR couples the hydrodynamics, species interactions, and heat transfer effects inside an ET plasma discharge. Recent enhancements of the THOR model and code allow for the estimation of heat transfer effects via a diffusion approximation for radiation heat transfer. Simulation results for both the original black-body radiation approximation and the diffusion approximation have been analyzed and compared. The black-body approximation produces better agreement with experiment for lower discharge energies (<3 kJ) while the diffusion approximation produces better agreement at higher discharge energies (>3 kJ). This is attributed to the increasing importance of the vapor shield layer that develops near the ablating surface inside ET plasma discharges at higher discharge energies. The diffusion approximation is shown to successfully simulate the effects of the vapor shield layer without the need for a tunable correction factor. The implementation of the diffusion

approximation for radiation heat transfer in the THOR code allows for the direct simulation of the vapor shield layer. This ability represents a significant advancement in the simulation and modeling capabilities available for ET plasma discharges and facilitates a deeper understanding of the underlying physics involved in these devices. This deeper understanding of the underlying physics will be an aid to researchers utilizing the high heat fluxes in ET plasma discharges to simulate disruption conditions in future fusion reactors.

Acknowledgments This work is made possible by the Nuclear Engineering Programs at Virginia Tech and The University of Florida. The authors acknowledge the resources provided by Advanced Research Computing at Virginia Tech and NSF grant CNS-0960081 and the HokieSpeed supercomputer at Virginia Tech.

References

1. N. AlMousa, L. Winfrey, J.G. Gilligan, M.A. Bourham, Radiative heat transport through vapor plasma for fusion heat flux studies and electrothermal plasma sources applications. *J. Nucl. Energy Sci. Power Gener. Technol.* **3**(1), 1–7 (2014)
2. M.A. Bourham, O.E. Hankins, O. Auciello, J.M. Stock, B.W. Wehring, R.B. Mohanti, J.G. Gilligan, Vapor shielding and erosion of surfaces exposed to a high heat load in an electrothermal accelerator. *IEEE Trans. Plasma Sci.* **17**(3), 386–391 (1989)
3. J. Eapen, *Theoretical and Numerical Foundations for Simulation of Ablative Plasma Flow in Electrothermal-Chemical Mass Accelerators*. Master's thesis (North Carolina State University, Raleigh, NC, 1998)
4. J.R. Echols, A.L. Winfrey, Surface effects of low incident angle, high heat flux plasma on tungsten utilizing an electrothermal source. Manuscript submitted for publication
5. J.R. Echols, A.L. Winfrey, Ablation of fusion materials exposed to high heat flux in an electrothermal plasma discharge as a simulation for hard disruption. *J. Fusion Energy* **33**, 60–67 (2014)
6. C.M. Edwards, M.A. Bourham, J.G. Gilligan, Experimental studies of the plasma-propellant interface for electrothermal-chemical launchers. *IEEE Trans. Magn.* **31**(1), 404–409 (1995)
7. M.J. Esmond, A.L. Winfrey, Estimation of transient effects of >2 mm radii in electrothermal plasma launchers for fusion fueling. *Trans. Am. Nucl. Soc.* **113**, 381–384 (2015). Washington, D.C., November 8–12, 2015
8. M.J. Esmond, A.L. Winfrey, Flow characteristics and charge exchange effects in a two-dimensional model of electrothermal plasma discharges. *J. Fusion Energy* **35**(2), 244–252 (2015)
9. T.E. Gebhart, R.T. Holladay, M.J. Esmond, A.L. Winfrey, Optimization of fusion pellet launch velocity in an electrothermal mass accelerator. *J. Fusion Energy* **33**(1), 32–39 (2014)
10. J. Gilligan, M.A. Bourham, The use of an electrothermal plasma gun to simulate the extremely high heat flux conditions of a tokamak disruption. *J. Fusion Energy* **12**(3), 311–316 (1993)
11. J. Gilligan, D. Hahn, R. Mohanti, Vapor shielding of surfaces subjected to high heat fluxes during a plasma disruption. *J. Nucl. Mater.* **162–164**, 957–963 (1989). doi:10.1016/0022-3115(89)90393-0
12. J.G. Gilligan, R.B. Mohanti, Time-dependent numerical simulation of ablation-controlled arcs. *IEEE Trans. Plasma Sci.* **18**(2), 190–197 (1990)
13. D. Hahn, J.G. Gilligan, Radiation transport through a plasma boundary layer between armatures and material surfaces. *IEEE Trans. Magn.* **27**(1), 251–256 (1991)

14. J.D. Hurley, M.A. Bourham, J.G. Gilligan, Numerical simulation and experiment of plasma flow in the electrothermal launcher sirens. *IEEE Trans. Magn.* **31**(1), 616–621 (1995)
15. E.Z. Ibrahim, The ablation dominated polymethylmethacrylate arc. *J. Phys. D Appl. Phys.* **13**, 2045–2065 (1980)
16. R.W. Kincaid, M.A. Bourham, Electrothermal plasma gun as a pellet injector. *J. Fusion Technol.* **26**(3), 637–641 (1994)
17. P. Kovitya, J.J. Lowke, Theoretical predictions of ablation-stabilised arcs confined in cylindrical tubes. *J. Phys. D Appl. Phys.* **17**, 1197–1212 (1984)
18. X. Li, R. Li, S. Jia, Y. Zhang, Interaction features of different propellants under plasma impingement. *J. Appl. Phys.* **112**(063303), 1–8 (2012)
19. R. Mohanti, *Time Dependent Numerical Simulation of Nonideal Plasmas in Ablation Controlled Arcs*. Ph.D. thesis (North Carolina State University, Raleigh, NC, 1990)
20. H. Ngo, M. Bourham, J. Doster, Heat and current transport in a metal-vapor electrothermal plasma source for electrothermal-chemical guns, in *35th JANNAF Combustion Subcommittee Meeting*, (Tucson, AZ, 1998), pp. 187–197
21. L. Niemeyer, Evaporation dominated high current arcs in narrow channels. *IEEE Trans. Power Appar. Syst.* **97**(3), PAS-950–958 (1978)
22. N. Orton, *Boundary Layer Energy Transport in Plasma Devices*. Ph.D. thesis (North Carolina State University, Raleigh, NC, 2000)
23. L. Pekker, Zero-dimensional time-dependent model of high-pressure ablative capillary discharge for plasma thrusters. *J. Propuls. Power* **25**(4), 958–969 (2009)
24. L. Pekker, O. Pekker, Model of high-pressure ablative capillary discharge for plasma thrusters. *J. Propuls. Power* **27**(2), 477–484 (2011)
25. A. Porwitzky, M. Keidar, I. Boyd, Progress towards an end-to-end model of an electrothermal chemical gun. *IEEE Trans. Magn.* **45**(1), 412–416 (2009). doi:[10.1109/TMAG.2008.2008688](https://doi.org/10.1109/TMAG.2008.2008688)
26. C.B. Ruchti, L. Niemeyer, Ablation controlled arcs. *IEEE Trans. Plasma Sci.* **PS-14**(4), 423–434 (1986)
27. M. Ryan, *The interaction of an electrothermal plasma with ja2 solid propellant*. Ph.D. thesis (The University of Texas at Austin, Austin, TX, 2006)
28. A.L. Winfrey, M.A. Al-Halim, A.V. Saveliev, J.G. Gilligan, M.A. Bourham, Enhanced performance of electrothermal plasma sources as fusion pellet injection drivers and space based mini-thrusters via extension of a flattop discharge current. *J. Fusion Energy* **32**, 371–377 (2013)
29. A.L. Winfrey, M.A.A. Al-Halim, J.G. Gilligan, A.V. Saveliev, M.A. Bourham, A study of plasma parameters in a capillary discharge with calculations using ideal and nonideal plasma models for comparison with experiment. *IEEE Trans. Plasma Sci.* **40**(3), 843–852 (2012)
30. A.L. Winfrey, J.G. Gilligan, M.A. Bourham, A computational study of a capillary discharge pellet accelerator concept for magnetic fusion fueling. *J. Fusion Energy* **32**, 227–234 (2013)
31. M.R. Zaghoul, Improved modelling of electrothermal plasma source with radiation transport. *J. Phys. D Appl. Phys.* **41**(225206), 1–10 (2008)
32. M.R. Zaghoul, M.A. Bourham, J.M. Doster, Semi-analytical modelling and simulation of the evolution and flow of ohmically-heated non-ideal plasmas in electrothermal guns. *J. Phys. D Appl. Phys.* **34**, 772–786 (2001)
33. Y. Zeldovich, Y. Raizer, *Physics of Shock Waves and High Temperature Hydrodynamic Phenomena*, vol. 1 (Academic Press, New York, 1966)