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14. ABSTRACT
The objective of this project was development and application of computational modeling approach for fundamental understanding of direct-current microdischarge phenomena. A detailed, two-dimensional plasma simulation tool has been developed and implemented for the study of microdischarges in the context of small-satellite electro-thermal propulsion. The special features of the model are a full self-consistent, multi-species, multi-temperature, treatment of plasma phenomena along with effect of a net bulk flow in the system. The particular geometry of the microdischarge based micropropulsion device defined the features of the computational model.

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Principal Investigator:
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Status of Effort:

The objective of this project was development and application of computational modeling approach for fundamental understanding of direct-current microdischarge phenomena. A detailed, two-dimensional plasma simulation tool has been developed and implemented for the study of microdischarges in the context of small-satellite electro-thermal propulsion. The special features of the model are a full self-consistent, multi-species, multi-temperature, treatment of plasma phenomena along with effect of a net bulk flow in the system. The particular geometry of the microdischarge based micropropulsion device defined the features of the computational model.

Accomplishments and New Findings:

Background:

Micropropulsion is an enabling technology for the operation of small satellites and can also fulfill precision thrusting requirements of larger conventional satellites. Essentially, micropropulsion devices can provide very low and controllable thrust levels (~10's-100's μN) and low impulse bits (~10's-100's μN-s). Scaling relationships for thruster parameters dictate that micropropulsion devices have geometric dimensions of order 10's to 100's of microns. Consequently new physical and chemical phenomena that are operative at these length scales must be reconciled with and exploited for the design of such devices.

We have recently proposed using direct-current (dc) microdischarges in an *electrothermal* class of micropropulsion device, called Microdischarge Plasma Thruster (MPT). Dc microdischarges are a class of highly stable, non-equilibrium, glow-like discharges that can be generated in extremely small geometric dimensions of order 10's to 100's of microns. These discharges are typically operated in noble gases at pressure of ~100 Torr, voltages of ~200 V, currents of ~10 mA (i.e. power ~1 to 10 W). Highly tunable gas heating ranging from room temperature to combustion-like temperatures of ~2000 K can be achieved in these discharges and this phenomenon is the basis for the MPT device concept. Figure 1 shows schematic of MPT device concept. The dc microdischarge is located just upstream of a micronozzle, where pressure can be maintained in the range of 100's Torr as required for discharge operation. A flowing gas is heated by the microdischarge and subsequently expanded through the micronozzle to produce thrust. The high stagnation temperatures achieved by the microdischarge heating significantly enhances the thruster specific impulse compared to a cold gas micronozzle thrusters.

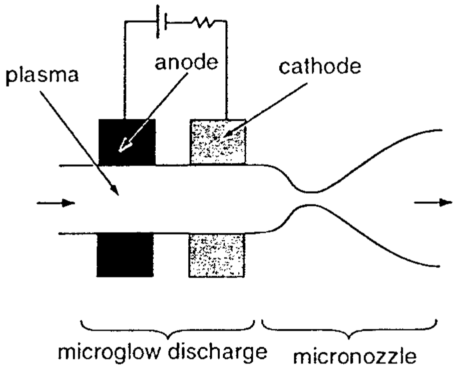


Figure 1: Schematic of Microdischarge Plasma Thruster (MPT) concept.

Objectives:

Our objective in the present research is to provide detailed understanding of physical and chemical mechanisms associated with dc microdischarge phenomena. A multidimensional, microdischarge computational model has being developed and employed for our studies. It is anticipated that fundamental insights provided by this study can be used in the development and optimization of a prototype MPT system. Additionally, fundamental insights into microscale plasma phenomena in general will be useful for a broader class of plasma-based microthruster concepts that are currently under investigation.

Results:

A microdischarge plasma simulator for study of MPT plasmas must include capability for simulation of 1) plasma dynamics as well as 2) bulk flow effects. An important consideration for the microdischarge plasma dynamics simulations is the fact that Debye lengths in the microdischarge plasmas are comparable to or often greater than geometric length scales in the system. Consequently, a self-consistent approach with capability of simulating both sheath and bulk plasma regions of the discharge (without making approximations such as quasineutrality) is necessary. This feature has significant effect on the numerical complexity of the problem with regards to temporal stiffness (e.g. electron timescales vs. heavy species and flow timescales). Other phenomena such as finite rate chemical kinetics also need to be included. The microdischarge simulator developed as part of this project, represents a fully self-consistent model of the discharge by solving multi species transport, multi-temperature phenomena, with Poisson's equation for the space-charge effects. The stiff system of equations is solved with a fully implicit Newton-Krylov sparse solver for robustness. We have determined that such fully implicit Newton solution methods are a necessary for successful solution of microdischarge phenomena over a broad range of parametric conditions. Bulk flow effects have also been included in our simulator and is necessary to capture the effect of plasma-bulk flow interactions.

Throughout this funded research program we have considered a simple microdischarge geometry with a blind hollow electrode structure without bulk flow and a through hollow electrode structure with bulk flow. The through hollow electrode structure is representative of the microdischarge heating zone shown in Fig. 1. The simulation studies for each of these geometries is discussed below.

Blind hollow microdischarges without bulk flow:

Microdischarge simulation results for stagnant gas are discussed below. The geometry chosen is a prototypical Micro Hollow Cathode Discharge (MHCD) as shown in Fig. 2. Helium gas is considered and a high-pressure helium chemistry with 6 species (e,He,He+,He2+,He*,He2*) and 9 reactions (electron impact ionization, electron impact excitation, deexcitation, stepwise ionization, Penning ionization, and three-body dimer production reactions) are included in the simulation.

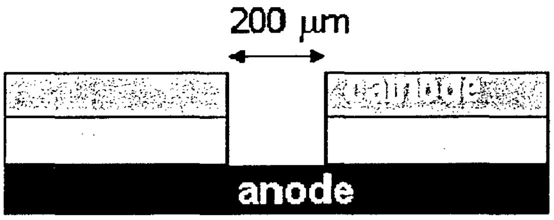
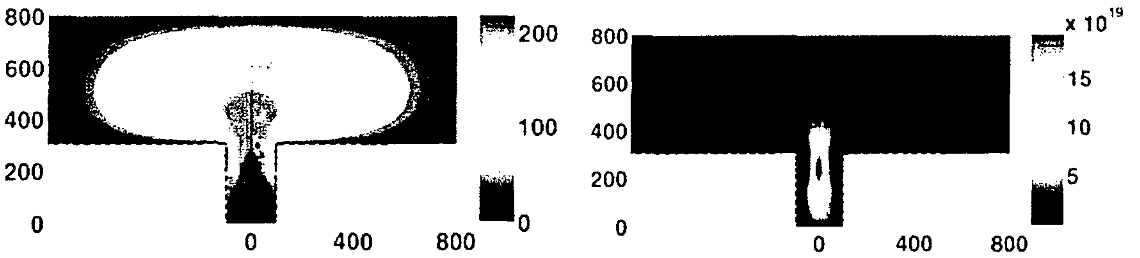


Figure 2: Schematic MHCD geometry used in computational studies.

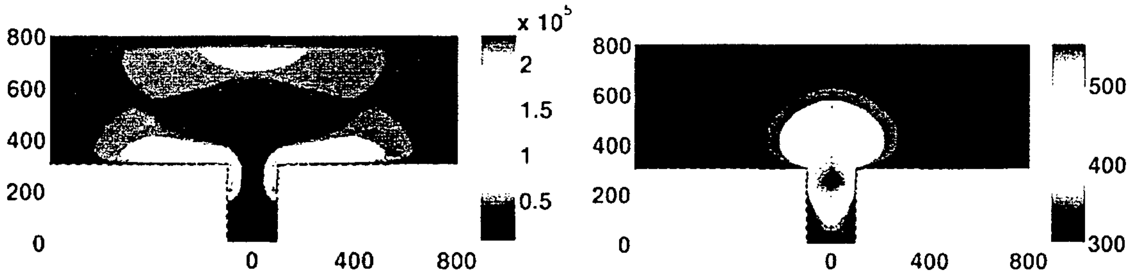
Figure 3 shows important plasma parameters for the MHCD at a pressure of 300 Torr and applied dc voltage of about 232 V in the helium plasma. The average current density for this case is about 2200 mA/cm2. Clearly in Fig. 3(a) a relatively thick cathode sheath region is discernible. The electron densities (Fig. 3(b)) reach peak values of order 1e19 (1/m3) which is significantly higher than in a classical glow discharge plasma.



(a) (b)

Figure 3: Contour plots of the MHCD a) plasma potential (V) and (b) electron number density (1/m3).

Figure 4 shows the electron temperature and gas temperature contours in the discharge. Electron temperatures are significantly high of order 2e5 K (~20 eV) in the cathode sheath region and are much lower of order a couple of eV in the bulk plasma region. The gas temperatures reach peak values in the center of the discharge in the vicinity of the cathode. Peak gas temperatures of about 600 K are observed. Although not shown here, the peak gas temperatures are highly controllable but increasing or decreasing the net current through the discharge and this aspect of the microdischarge offers principal advantage for realizing a variable specific impulse microthruster (by using discharge current as a knob).



(a) (b)

Figure 4: Contour plots of the MHCD (a) electron temperature (K) and (b) gas temperature (K).

Through hollow electrode microdischarge with bulk flow effects:

For the through hollow case the computational domain is shown in Fig. 5. The computational grid used for the simulation is also shown in the same figure. A Cartesian mesh with approx 70x40 grid points are used for the simulations.

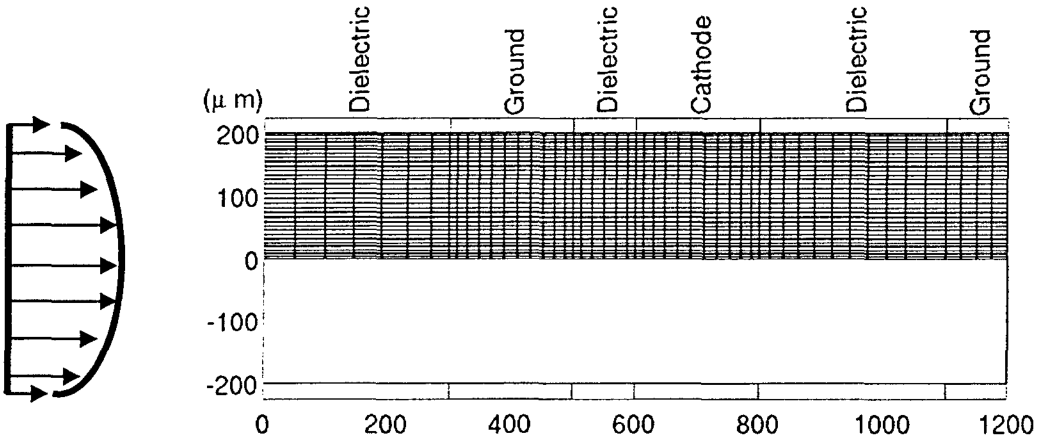


Figure 5: Computational domain and grid used for simulation of through hollow electrode microdischarge geometry.

In Fig. 6, we show the voltage-current (V-I) characteristics for the discharge as a function of system pressure and the bulk flow rates in the system. The main feature of the V-I characteristics is the positive differential resistivity of the discharge. The positive differential resistivity is indicative of an abnormal glow discharge, which is apparent given the finite electrode area available to the discharge in this configuration. As pressure increases the differential resistivity of the discharge decreases and also the total resistance of the discharge decreases. An increase in the bulk flow rates through the discharge has the same effect as an increase in the pressure.

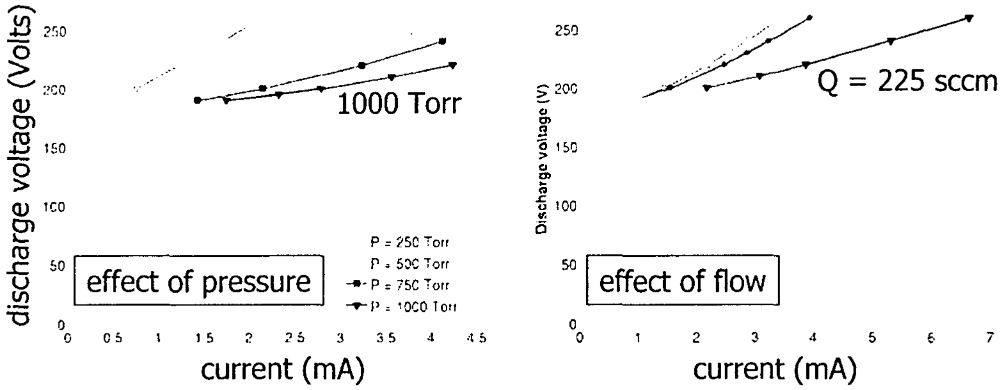


Figure 6: V-I characteristics of the microdischarge as a function of pressure and bulk flow rates.

Figure 7 shows electric potential contours and the space charge density contours for the discharge. A cathode sheath is clearly discernable from both figures. The sheath thickness of about 100 microns is observed which is a significant fraction of the overall discharge volume. This fact is the principal reason that a full self consistent model is necessary for our simulation studies.

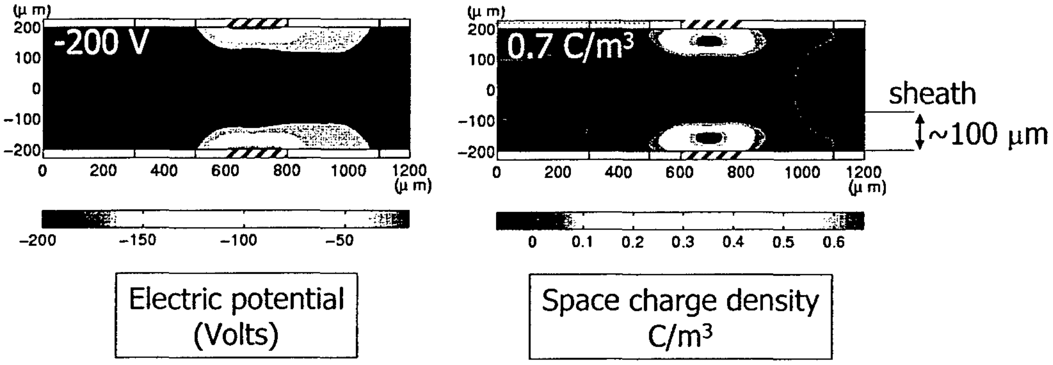


Figure 7: Electric potential and sheath structure for through hollow microdischarge.

Figure 8 shows the electron density contours for the microdischarge in the absence of flow as well as in the presence of flow. The peak electron densities in both cases are of order 1e19 /m3 which is significantly larger than a typical glow discharge and is yet smaller than an arc. This feature emphasizes the fact that properties of microdischarge are somewhat intermediate between a glow and an arc. In the absence of flow the electron density is center peaked while in the presence of flow the contours become off-center peaked, indicating significant effect of bulk flow on the discharge properties.

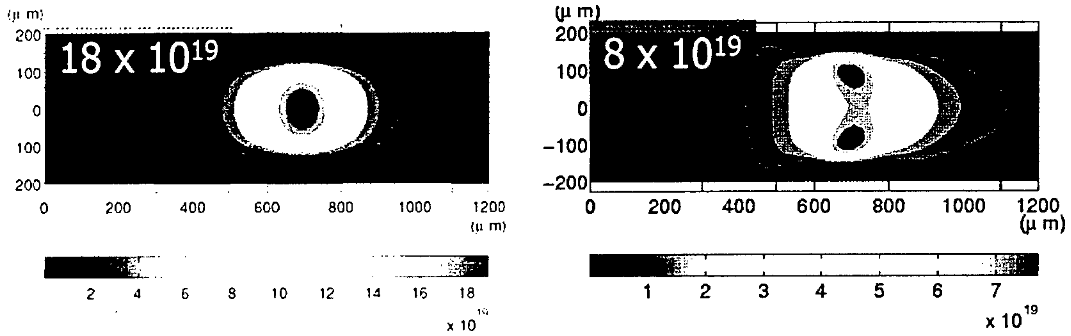


Figure 8: Effect of flow on the electron density contours in the through hollow microdischarge. Left figure is without flow and right figure is with 225 sccm flow.

Finally, the gas temperature in the discharge is presented in Fig. 9 along with the bulk flow velocity profiles. Peak gas temperatures of around 700 K are observed emphasizing the significant gas heating in microdischarges. This feature is key to the microdischarge application. While a small speedup is observed in the bulk velocity, this increase is not important since the MPT concept requires gas heating that can in turn be utilized in the electro-thermal propulsion application.

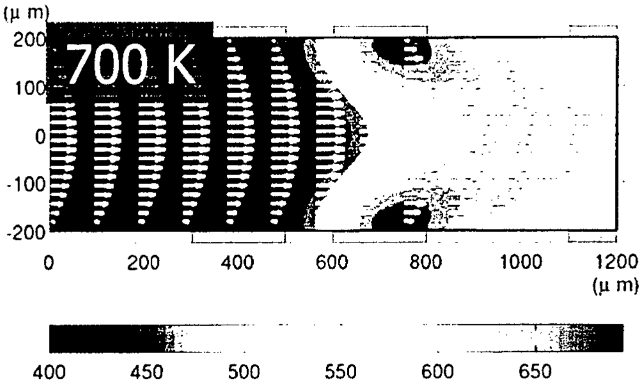


Figure 9: Gas temperatures and bulk flow velocity profiles in the through hollow microdischarge.

Future work:

It is important that the current computational work is validated and therefore a concerted experimental program that is fundamental based is necessary. The present study is focused on helium as a propellant, but other gases such as heavier argon or xenon and even molecular gases may be important and must be considered in future studies. The issue of low Reynolds number effects are emphasized by the loss in gas temperatures as the bulk gas flows through the discharge. Novel heat recuperation techniques may therefore be necessary in an actual MPT system. Finally, the non-thermal effects, (electrostatic and electromagnetic) may be able to improve performance of the system and must be considered for MPT.

Personnel supported:

L. L. Raja – Assistant Professor, The University of Texas at Austin (1 mo. summer per year)
P. S. Kothnur – Graduate Research Assistant (Ph.D), The University of Texas at Austin

Publications:

Journal:

1. P. Kothnur, X. Yuan, and L. L. Raja*, "Structure of Direct-Current Microdischarge Plasmas in Helium," *Applied Physics Letters*, Vol. 82, No. 4, Jan. 2003, pp. 529-531.
2. P. S. Kothnur and L. L. Raja*, "Two-Dimensional Simulation of a Direct-Current Microhollow Cathode Discharge," *Journal of Applied Physics*, Vol. 97, Feb. 2005, pp. 043305-1-12.
3. P. S. Kothnur, J. Shin, and L. L. Raja*, "Experimental and Numerical Study of External Plume Characteristics in Microhollow Cathode Discharges," *IEEE Transactions on Plasma Science*, Vol. 23, No. 2, Apr. 2005, pp. 564-565. (4th Triennial Special Issue on Images in Plasma Science).
4. P. S. Kothnur and L. L. Raja*, "Simulation of direct-current microdischarges for application in electro-thermal class of small satellite propulsion devices," *Contributions to Plasma Physics*, (submitted).

Conference papers and talks:

1. P. Kothnur, X. Yuan, L.L. Raja, "One-dimensional Simulation of Glow-Like Plasma Phenomena in Parallel-Plate Microdischarge Geometries," Gordon Research Conferences, Tilton School, NH, July 21-26, 2002.
2. P. Kothnur, X. Yuan, and L.L. Raja, "One-Dimensional Simulation of Glow-Like Plasma Phenomena in Parallel-Plate Microdischarge Geometries," 49th International Symposium, American Vacuum Society, Denver, CO, Nov. 3-8, 2002.
3. P. S. Kothnur and L. L. Raja, "Two-Dimensional Simulation of the Structure of Direct-Current Microdischarges," 56th Gaseous Electronics Conference, San Francisco, CA, Oct. 21, 2003.
4. P. S. Kothnur and L. L. Raja, "Two-Dimensional Simulation of the Structure of Direct-Current Microdischarges," 50th International Symposium, American Vacuum Society, Baltimore, MD, Nov. 5, 2003.

5. P. S. Kothnur and L. L. Raja, "Two-Dimensional Simulation of the Structure of Direct-Current Microdischarges," 42nd AIAA Aerospace Sciences Meeting and Exhibit, Reno, NV, Jan. 5-8, 2004.
6. P. S. Kothnur and L. L. Raja, "Two-Dimensional Computational Modeling of the Structure of Direct-Current Microdischarges," AIAA Paper 2004-987, 42nd AIAA Aerospace Sciences Meeting and Exhibit, Reno, NV, Jan. 5-8, 2004.
7. P. Kothnur and L. L. Raja, "Two-Dimensional Simulations of Interactions Between Bulk Flow and Plasma Dynamics in Direct-Current Microdischarges," 17th International Symposium on Plasma Chemistry, Toronto, Canada, Aug. 7-12, 2005.
8. P. S. Kothnur and L. L. Raja, "Simulation of Microdischarge Gas Heating in Electro-Thermal Class of Small Satellite Propulsion Devices," 58th Gaseous Electronics Conference, San Jose, California, Oct. 16-20, 2005.
9. L. L. Raja, "Simulation of Direct-Current Microdischarges for Small-Satellite Micropropulsion Applications," **(Invited Talk)** Mechanical and Aerospace Engineering Department Colloquium, Cornell University, Ithaca, NY, Nov. 22, 2005.

Interactions/Transitions:

A prototype Microdicharge Plasma Thruster device is currently being developed for implemented in a university nanosatellite that is being funded by AFRL as part of another project. This project is a collaboration between Prof. Lightsey and Prof. Raja in the department of Aerospace Engineering and Engineering Mechanics at the University of Texas at Austin. The design of this MPT device benefits significantly from insights provided by the current computational study. The PI is also in conversation with Dr. Bill Hargus of AFRL-Edwards AF Base to explore the possibility of testing these devices in their laboratory.

Honors/Awards:

Prior - NSF-CAREER award, 2001.