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Direct Simulation Monte Carlo Analysis of Microscale Field Emission and Ionization of Atmospheric Air

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ABSTRACT
Ionic winds are formed when air ions are drawn through the atmosphere by applied electric and/or magnetic fields. The ions collide with neutral air molecules, exchanging momentum, causing the neutral molecules to move. Continued collisions and momentum exchanges generate a net flow called an ionic wind [1]. Ionic winds formed near flat plates can produce local boundary layer distortion in the presence of a bulk flow. This concept has been studied experimentally at the macroscale as a method for drag reduction [2] and has been suggested at the microscale for convective cooling enhancement [3]. Specifically, microfabricated ion wind engines can be integrated onto electronic chips to provide additional local cooling at “hot-spot” locations. In our previous work, continuum modeling of the ionic wind phenomena showed an approximately 50% increase in the local heat transfer coefficient at the location of the ion wind engine [3]. However, in that work, ionization physics were not modeled, rather assumptions for ion current and concentrations were used as a basis for modeling ion transport.

At the microscale, ionization occurs when field-emitted electrons from closely spaced electrodes collide with neutral air molecules, stripping away electrons and forming molecular ions. Geometric enhancement of the electrodes using nanostructured materials enables low ionization voltages conducive to microelectronic devices. Understanding the microscale ionization process is necessary to accurately predict the ensuing ionic wind and cooling. Direct Simulation Monte Carlo (DSMC) is used in the present work to predict field emission between two planar electrodes and the consequent ionization of the interstitial air.

NUMERICAL SIMULATION
Figure 1 shows a cross-sectional schematic of an ion wind engine in the presence of a bulk flow. Previous experimental work by Schlitz on microscale ionic winds suggests that ions are often trapped on the dielectric surface between the electrodes, reducing the ion density in the air and the ensuing body force on the bulk flow [4]. The two electrodes depicted in Figure 1 are elevated above the surface in order to reduce ion trapping. The DSMC simulation predicts ion and electron currents to the electrodes and to the flat plate, thus quantifying ion trapping.

Figure 1 Cross-sectional view of microscale ion wind engine. Boundary layer distortion due to the ionic wind is depicted with the downstream profile. The electrodes are 20 µm wide by 1 µm high and spaced 10 µm apart. The electrodes are elevated 10 µm above the flat plate. (Not to scale.)

DSMC techniques simulate many particles (hundreds of thousands or more) in groups in order to represent a much larger number of real particles. A potential is applied between the two electrodes, and the resulting electric field, determined by Poisson’s equation, causes electron field emission from the cathode. The electrons are accelerated through the gap between electrodes by the electric field, and collisions (including ionizations) with neutral air molecules are simulated and tracked statistically. Any generated electrons from ionization processes and the movement and collisions of the air ions are also traced.

Field emission is modeled using Fowler-Nordheim theory [6] in which the surface current density is given by
The emitted electron current is predicted to be 0.1095 mA based on Eq. (1) (using typical $\phi$ and $\beta$ values for nickel plates) and the simulated current is 0.1089 mA. As shown in the figure, the electrons emit from the left face of the cathode and travel across the gap to the anode, ionizing the neutral air in the process. Note that the trajectories of the electrons and ions do not exactly follow the field lines due to random collisions. The elevation of the electrodes 10 µm above the flat plate minimizes ion trapping at the surface, and the size of the ion cloud suggests that the electrodes must be at least 4 µm above the surface. The ratio of ions to emitted electrons is 2.91, indicating that at this potential difference the ion current is nearly three times the emitted electron current.

CONCLUSIONS & FUTURE WORK

A DSMC simulation of an ion wind engine with elevated electrodes predicts the electron field emission and ensuing ionization of the interstitial air. The form of the ion clouds indicate that elevating the electrodes above the dielectric surface will reduce the impact of ion trapping at the surface. Microscale fabrication of ion wind engines will incorporate elevated electrodes based on these results. Additionally, the simulation indicates the amount of ionization relative to the emitted electron current for this parallel electrode configuration at an applied potential of 460 V. Ongoing numerical work will incorporate the results of the DSMC simulations as ion concentration and current boundary conditions in future continuum simulations of ion transport and ionic winds.

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REFERENCES


Figure 2 Townsend’s first ionization coefficient (divided by pressure) versus the applied electric field to pressure ratio ($E/P$) from the present work, Zhang et al.’s simulation [8], and experimental results [9].

Figure 3 DSMC simulation at 10 ps showing the electron, N$_2$ ion and O$_2$ ion clouds. Note that the two ion clouds partially obscure the electron cloud, and the O$_2$ ion cloud partially obscures the N$_2$ ion cloud.


