Coupled-Physics Modeling of Electrostatic Fluid Accelerators for Forced Convection Cooling

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Classic thermal management solutions are becoming inadequate and there is an increasing need for fundamentally new approaches. Electrohydrodynamic ionic wind pumps, also known as electrostatic fluid accelerators (EFA), have the potential for becoming a critical element in electronics thermal management solutions. As the EFA field continues to evolve, developing new EFA-based technologies will require accurate models that can help predict pump performance metrics, such as air velocity profile, back pressure, and cooling efficiency. Many previous modeling efforts only account for electrostatic interactions. For truly accurate modeling, however, it is important to include effects of fluid dynamics and space charge diffusion. The modeling problem becomes especially challenging for the design and optimization of EFA devices with greater complexity and smaller dimensions. This paper presents a coupled-physics finite element model (FEM) that accounts for space charge generation from a corona discharge, as well as space charge diffusion and fluid dynamic effects in EFAs. A cantilever EFA structure is modeled and analyzed for forced convection cooling. Numerical modeling predicts maximum air velocities of approximately 7 m/s and a maximum convection heat transfer coefficient of 282 W/(m²K) for the cantilever EFA structure investigated. Preliminary experimental results for a microfabriacted cantilever EFA device for forced convection cooling are also discussed.

Nomenclature

A_s	=	area of surface S
C_p	=	specific heat capacity
D	=	diffusivity of air ions
$\mathbf{E}$	=	electric field intensity
E_e	=	electric field strength at the surface of corona electrode
E_0	=	breakdown electric field strength of air
h_{ave}	=	average convection heat transfer coefficient
I_c	=	ion current leaving the ionization zone
$\mathbf{J}$	=	current density
k	=	thermal conductivity

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p	=	air pressure
q	=	space charge density
Q	=	heat flux in watts
R_0	=	distance from the center of the corona electrode tip to the ionization zone
R_e	=	radius of corona electrode tip
S	=	an arbitrary surface
T	=	temperature in degrees Kelvin
T_{sa}	=	substrate to ambient temperature differential in degrees Kelvin
$\mathbf{U}$	=	Velocity vector
V_0	=	electric potential at the external boundary of the ionization zone
V_e	=	electric potential at the surface of the corona electrode
ϵ_0	=	dielectric permittivity of free space
μ_E	=	ion mobility in air
μ	=	dynamic viscosity
	=	air density

I. Introduction

The problem of thermal management in microelectronics is at the center of attention of academia, government agencies, and industry worldwide. Rapid development of microelectronics has led to an immense component density. Within this decade the size of a single component will decrease to nearly 25 nm. This in turn will amplify the already existing problem, which is that each semiconductor component emits heat associated with the electrical resistance, leading to a large heat flux from a shrinking surface area. Meanwhile, the progress in MEMS and power electronics is also affected by the bottleneck of heat removal. In high-speed MEMS applications, new issues include the mechanical heat generation due to friction and the introduction of combustion processes in microdevices. In power electronics, high current applications create high heat fluxes that require dramatic improvement in heat dissipation methods. Existing cooling devices are no longer efficient in terms of energy consumption and heat removal. The decreasing size of microelectronics components and the increasing thermal output density requires a dramatic increase of thermal exchange surface from classic heatsink/rotary fan assemblies. However, simple growth of heatsink area is no longer a viable option for most applications. Elaborate cooling systems are being developed, including those using phase change heat pipes, liquid cooling, refrigeration, novel thermal interface materials (TIM), and Peltier devices to spread the heat from high heat flux areas,¹ but the last step of heat exchange with the ambient environment always remains necessary.

Classic rotary fans have been used for forced convection over the last few decades and are still used to enable the final heat exchange with the ambient. The classical rotary structural geometry, although used in numerous applications, is limited in both scale and design flexibility, due to the necessity of high-speed rotating parts. Turbulent flow, vibration, and gyroscopic forces introduce inherent inefficiency and noise to a rotary system. Even in the applications for which acoustic noise and vibrations do not present a significant problem, rotary fans are difficult to optimize for more than a single air flow circulation pattern, due to their nearly static cross-sectional air velocity profile. Electrostatic fluid accelerators (EFAs) offer nearly laminar air propulsion with dynamic airflow profiles, controllable air velocities, and a possibility to decrease the effective boundary layer at the solid-fluid interface.^{2,3} In addition, EFA propulsion is achieved without moving mechanical parts, thus enabling flexible design and possible integration at the MEMS level.^{4,5}

As the EFA field continues to evolve, there is a growing need for accurate models that can help predict pump performance metrics, such as air velocity profile, back pressure, and cooling efficiency. Many previous modeling efforts only account for electrostatic interactions.⁶⁻⁸ For accurate modeling, however, it is important to include effects of fluid dynamics and space charge diffusion. Preliminary coupled-physics modeling has been conducted in one-dimensional space without accounting for charge generation,^{4,9} showing good agreement with analytical models for a simple one-dimensional space.¹⁰ The modeling problem becomes especially challenging for design and optimization of EFA devices with high geometric complexity and small scale. The heat transfer and EFA flow characteristics are analyzed using a two-dimensional coupled-physics finite element method model that accounts for charge generation, space charge diffusion, and fluid dynamic effects. Preliminary results from a proof of concept microfabricated EFA device are also analyzed.

II. Background

The mechanism of corona-induced ionic wind propulsion is illustrated in Figure 1. Gas molecules near the corona discharge region become ionized when a high intensity electric field is applied between a high tip curvature corona electrode and a low tip curvature collector electrode. In the case of a wire or rod electrode, the diameter of the electrode is equivalent to the tip curvature of a needle electrode. The ionized gas molecules travel towards the collector electrode, colliding with neutral air molecules. During these collisions, momentum is transferred from the ionized gas into the neutral air molecules, resulting in the movement of gas towards the collector electrode. The operating voltage range for corona discharge lies between the corona onset and the air gap breakdown voltage.¹¹ Corona induced airflow is possible with both positive and negative voltages. It has been reported that higher stream velocity can be achieved by using positive polarity.¹² In general, the selection of polarity depends on a large number of factors, which include electrode material, device geometry, ozone generation constraints, and others. The governing equations describing the interaction of electric charges with moving media in an electrostatic fluid accelerator have been known for a long time. Comprehensive reviews and tutorials on this subject are readily available.^{11,13-18}

Figure 1. Ion stream of a DC electrostatic air pump, where a high voltage is applied between the corona and collector electrodes.

III. Modeling of EFA

A. Governing equations for electrohydrodynamic flow

Electrohydrodynamic flow induced by corona discharge and the resulting heat transfer is described by the following equations. The electric potential V is governed by the Poisson's equation

$$\nabla^2 V = -\frac{q}{\epsilon_0} \quad (1)$$

where q is the space charge density and ϵ_0 is the dielectric permittivity of free space. The electric potential is defined from electric field intensity $\mathbf{E}$ as

$$\mathbf{E} = -\nabla V \quad (2)$$

Electric current in the drifting zone is a combination of three effects: conduction (motion of ions under electric field relative to entire airflow), convection (transport of charges with airflow), and diffusion. Therefore, current density $\mathbf{J}$ is given by

$$\mathbf{J} = \mu_e \mathbf{E} q + \mathbf{U} q - D \nabla q \quad (3)$$

where μ_e is the air ions mobility in an electric field, $\mathbf{U}$ is velocity vector of airflow, and D is the diffusivity coefficient of ions. Current continuity condition gives equation for current density

$$\nabla \cdot \mathbf{J} = 0 \quad (4)$$

The hydrodynamic part of the problem is described by the Navier-Stokes equations and momentum continuity equation for steady state incompressible air flow

$$\rho \mathbf{U} \cdot \nabla \mathbf{U} = -\nabla p + \mu \nabla^2 \mathbf{U} - q \nabla V \quad (5)$$

$$\nabla \cdot \mathbf{U} = 0 \quad (6)$$

where ρ is the air density, p is the air pressure, and μ is the air dynamic viscosity.

Heat transfer then can be described by thermal conduction and convection

$$\mathbf{Q} = \nabla \cdot (-k \nabla T) + \rho C_p \mathbf{U} \cdot \nabla T \quad (7)$$

where $\mathbf{Q}$ is the heat flux, k is the thermal conductivity of the medium, T is the temperature, ρ is the density of the air, and C_p is the specific heat capacity of air.

The system of equations (1), (4), (5), (6), and (7) is subject to appropriate boundary conditions described below for the EFA forced convection heat transfer model investigated in this study.

B. Space charge generation

Space charge generation by corona discharge in an EFA device can be modeled by applying appropriate electrostatic and charge transport boundary conditions at the surface of the ionization zone. A description of the boundary conditions for space charge generation estimation is described in this section.

The gap between corona and collecting electrodes can be divided into two regions, the ionization and drift zones. The ionization zone exists in close proximity to the corona electrode, in which air ionization occurs, and both positive and negative ions exist. The drift region, located between the ionization region and the collector electrode contains ions of a single polarity that have been driven out of the ionization region by the electric field. When the radius of the corona electrode is much smaller than the distance between corona and collecting electrodes, the ionization zone forms a uniform sheath over the coronating region of the corona electrode surface. For the positive corona, the electric field strength E_e at the surface of a smooth corona electrode of radius R_e is given by Peek's empirical formula for air at standard conditions¹¹

$$E_e = E_0 \left(1 + 2.62 \cdot 10^{-2} / \sqrt{R_e}\right) \quad (8)$$

where the corona electrode radius R_e is measured in meters and $E_0 = 3.23 \cdot 10^6$ V/m is the breakdown (ionizing) electric strength of air. In contrast with the drifting zone, the net space charge density is negligible in the ionization zone since it contains charges of both polarities in similar magnitudes. Thus, assuming the electrode tip radius is much smaller than the distance between corona and collecting electrodes, the electric potential and electric field intensity inside the ionization zone are

$$V = V_e - E_e R_e \ln \frac{r}{R_e} \quad (9)$$

$$E = E_e \frac{R_e}{r} \quad (10)$$

where V_e is the voltage at the electrode surface, and V is the voltage at a radius r from the center of the corona electrode tip within the ionization region. At the boundary between the ionization and drifting zones, the electric field strength is equal to the breakdown electric field strength E_0 . Using Eq (9) and Eq (10), the external radius of the ionization zone can be estimated:

$$R_0 = R_e E_e / E_0 = R_e \left(1 + 2.62 \cdot 10^{-2} / \sqrt{R_e}\right) \quad (11)$$

The voltage drop through the ionization zone can be found by integrating the electric field strength from R_e to R_0 . As the result, the voltage on the external boundary of the ionization zone is given by

$$V_0 = V_e - E_e R_e \ln \frac{E_e}{E_0} \quad (12)$$

At the external surface of the ionization zone, Kapsov's assumption is used,¹⁹ which states that the ionization zone radius remains approximately constant with V_e once a corona is formed. This enables estimation of the surface charge density by specifying the electric field strength: $E = E_0$ at $r = R_0$. Therefore, space charge generation due to corona discharge can be estimated by prescribing voltage V_0 to the external surface of the ionization zone at a radius R_0 from the center of the corona electrode tip to satisfy Poisson's equation. The charge transport equation is similarly satisfied by applying a surface charge density at the external surface of the ionization zone such that the resulting electric field at that surface located at a radius R_0 is equal to the breakdown field intensity E_0 .

IV. Numerical model and procedure

A high tip curvature cantilever beam suspended over a flat conductive thermal exchange surface, shown in Figure 2, was used as the basis for the EFA-induced heat transfer modeled in this study. A DC voltage is applied between the corona electrode and conductive thermal exchange surface creating ions at the tip

Figure 2. Diagram of cantilever EFA device structure and operation.

of the cantilever. The ions are accelerated towards the thermal exchange surface creating an air jet along their path, resulting in forced convective thermal transfer from the substrate. The cantilever EFA design, although not necessarily optimal for cooling, was chosen due to its relative ease of modeling as well as ease of fabrication and ease of experimental analysis with IR imaging. The three-dimensional cantilever EFA structure shown in Figure 2 can be approximated by the two-dimensional model shown in Figure 3, where the device is reduced to a single cross-sectional plane taken across the end of the cantilever as depicted in Figure 3 (a) and (b). The simplified two-dimensional model makes a number of assumptions, including reducing the cantilever tip to a circular cross-section, and effectively ignoring the electric field and fluid dynamics contribution by the rest of the cantilever structure. However, these approximations will lead mainly to second order effects in IV characteristics and air jet shape. The EFA-induced heat transfer was numerically modeled in FEMLAB, a finite element modeling suite, using the steady-state coupled physics modeling approach outlined previously using Eq (1) through Eq (12).

The numeric simulation space, subdomains, and boundaries are shown in Figure 4. The simulation space was broken into two subdomains, the ionization and drift zones. The ionization zone, shown in Figure 4, is the region between the surface of the corona electrode and the ionization zone boundary. The drift zone then is the remaining area between the ionization zone boundary and

the substrate. The substrate, although shown in Figure 4 for illustration, was not a subdomain but was accounted for by application of appropriate boundary conditions at its interface with the drift zone.

Electrical domain equations were solved only within the drift zone subdomain, while the fluid dynamics and heat transfer equations were solved within both the drift and ionization zone subdomains. Although the net charge within the ionization zone is negligible and thus no additional body force is applied to the air within the ionization zone, the Navier-Stokes equations are solved there in order to account for the actual electrode tip geometry rather than the larger size of the ionization zone. The subdomain modeling parameter values are shown in Table 1.

Boundary conditions applied to the numerical model, are shown in Table 2 and are as follows. For

Figure 3. Two cross-section views of the EFA device are shown in (a) and (b). The dashed line in (a) shows the location of the plane of cross-section that is displayed in (b). The simulation space used to model the EFA is shown in (b), where the corona electrode tip cross-section is approximated as a circle. Model dimensions not drawn to scale.

Table 1. Sub-domain modeling parameter values used in FEM modeling

Modeling parameter	Value
Relative dielectric permittivity of air	1
Charge diffusion coefficient	2.66E-05
Ion mobility coefficient	2.1e-4 m ² /(Vs)
Density of air	1.105 kg/m ³
Kinematic viscosity of air	1.8e-5 m ² /s
Heat capacity of air	1.007 kJ/(kgK)
Thermal conductivity of air	27.7e-3 W/(mK)
Corona electrode to substrate separation	3mm
Corona electrode tip radius	50μm

Table 2. Boundary conditions used in FEM modeling

Boundary	Electrostatics	Charge transport	Fluid dynamics	Heat transfer
Substrate	grounded	Zero diffusive flux	No-slip	Constant Temperature 60 C
Corona electrode	Voltage applied only to ionization boundary (V_0), which is based on applied corona electrode voltage, Eq(12), of 3.5 to 6.5 kV	N/A	No-slip	Constant Temperature 26 C
Air boundaries	ABC	Zero diffusive flux	Neutral pressure	Convective flux*
*Air boundary under EFA air jet (Sets ambient air temperature)	ABC	Zero diffusive flux	Neutral pressure	Constant Temp 25 C
Ionization boundary	Voltage V_0 and electric field intensity E_0	Surface charge density solved by simulation	N/A	N/A

Figure 4. FEMLAB simulation space, showing geometry and location of corona electrode tip and ionization zone boundary in relation to substrate. Schematic dimensions not drawn to scale.

electrostatics, a constant positive DC voltage V_0 was applied to the ionization zone surface, and zero volts were applied to the substrate/thermal exchange surface. All other boundaries were set to an absorbing boundary condition (ABC). For charge transport, a space charge surface density is applied to the surface of the ionization zone, calculated using Eq (8) to Eq (12). A zero diffusive flux condition is imposed on all boundaries except for the external surface of the ionization zone. The validity of this assumption is justified by the fact that the diffusion term is very small compared to the conduction term in Eq (4) and can be set to zero at the boundaries with negligible effect.^{22,23} For fluid dynamics, a no-slip condition is applied to the surface of the substrate and corona electrode, and a neutral pressure condition is assigned to all air boundaries. The heat transfer problem was solved by applying a constant temperature to the substrate, corona electrode surface, and air boundaries which had a net influx of air into the model. A convective flux boundary condition was applied to all other external air boundaries.

V. Numerical Results

Numerical simulations results for the cantilever EFA design correlated well with the expected electric field profile, charge distribution, air jet velocity, jet shape, and the resulting heat transfer. Surface plots of a cantilever EFA with a three-millimeter separation shown in Figure 5 display the solutions to the four coupled physical phenomena modeled: electrostatics, charge transport, fluid dynamics, and heat transfer in Figure 5 (a, b, c, and d). The plots shown in Figure 5 were generated using modeling parameters in Table 1, Table 2, and a corona electrode to substrate electric potential difference of 5.5 kV.

The electric potential and corresponding electric field, Figure 5 (a), match the expected shape and profile decreasing in magnitude from the edge of the ionization zone to the substrate. The light shaded half-circle over the corona electrode represents the ionization zone, which was not part of the solution space for electrostatic or charge transport calculations, as explained previously. The space charge, generated within the ionization zone and accelerated through the drift zone, is distributed with high density near the ionization zone and decreasing slowly towards the collector, with the space charge density falling off faster in the x direction to the left or right of the corona electrode. Thus, the ion stream has its largest component in the y direction directly above the ionization region traveling from corona to substrate, Figure 5 (b). The traveling ion stream induces an air jet along its path that impinges on the substrate surface as seen in Figure 5 (c), with the greatest y -directional air velocities centered directly above the ionization region in the area of the highest

Figure 5. EFA simulation results: (a) electric potential as colored surface map and electric field arrows, (b) normalized space charge density as a colored surface map and columbic force as arrows, (c) air velocity as a colored surface map and air velocity as arrows. (d) air temperature as a colored surface map and air velocity as arrows. Arrows in all figures scaled linearly.

Figure 6. EFA simulated ion current, I_c , vs. applied corona electrode voltage V_e , plotted on the left vertical axis. EFA power vs. applied corona electrode voltage V_e plotted on the right vertical axis.

space charge density. The impinging air jet decreases the fluid and thermal boundary layer thickness, producing the thermal boundary layer shown in Figure 5 (d), which is thinnest at either side of the air jet and increases moving away from the center.

The ion current, I_c , leaving the ionization zone can be calculated by multiplying Eq (3) by the area of the ionization zone surface with the electric field at the boundary of the ionization zone equal to E_0 . It was assumed for the cantilever structure that approximately one half hemisphere of the cantilever tip would have an active corona region with an area of $3.62 \times 10^{-7} \text{ m}^2$. The current-to-voltage characteristics of the cantilever EFA follow the expected exponential current dependence on the electric potential between corona electrode V_e and substrate⁶ as shown in Figure 6, with I_c increasing from 9.6×10^{-8} amperes to 4.6×10^{-6} amperes over a V_e range of 3.5kV to 6.5kV. The device power rises exponentially with the applied voltage

due to the exponential increase in current. A linear positive relationship was observed between EFA air jet velocity and V_e , as shown in Figure 7. Simulated air velocities fell within the range of velocity magnitudes reported from experimental analysis.⁶ The EFA air jet y-directional component velocity was averaged over three cross-sections, each centered over the corona electrode and positioned one millimeter above the bottom of the solution domain in Figure 5. The three cross-section lengths chosen were one, eight, and twenty millimeter(s). The average air velocity over the 1 mm cross-section ranged from approximately 1 m/s to 7.6 m/s with the highest velocity at a V_e of 6.5 kV. The EFA-induced air jet is focused around a 1 mm cross-section, with the average airflow for a 20 mm cross-section falling to 0.15 m/s and 1.14 m/s for and applied V_e of 3.5 kV and 6.5 kV respectively.

The average convective heat transfer coefficient h_{ave} can be calculated by

$$h_{ave} = Q / (A_s \Delta T_{sa}) \quad (13)$$

where Q is the thermal power in watts removed from a surface S , A_s is the area of surface S , and T_{sa} is the temperature difference in Kelvin between S and the ambient air. The average convective heat transfer coefficient along the substrate scaled approximately linear with increasing applied voltage V_e as shown in Figure 8. The average heat transfer coefficient was calculated at the surface of the substrate over four circular disk shaped areas, each centered above the corona electrode. Disk shaped surface areas with diameters of one, two, three, and eight millimeter(s) were used for the calculation. The highest h_{ave} of 282 $\text{W}/(\text{m}^2\text{K})$ was over the one millimeter disk at the maximum applied voltage of 6.5 kV. The value of h_{ave} was relatively constant at a disk size of one to three millimeter(s) but dropped off up to 38.5 percent over the eight millimeter disk at the highest V_e . Notably, these

Figure 7. Simulated EFA air jet y component velocity vs. applied voltage V_e averaged over three cross-section distances one millimeter above the bottom of the numerical solution domain shown in Figure 5.

Figure 8. Simulated convective heat transfer coefficient h_{ave} vs. applied voltage V_e . h_{ave} calculated over four circular disk shaped areas on the substrate centered above the corona electrode. Disk diameters of one, two, three, and eight millimeter(s) were used.

Figure 9. Simulated cooling efficiency in percent vs. applied voltage V_e . Cooling efficiency calculated over four circular disk shaped areas on the substrate centered above the corona electrode. Disk diameters of one, two, three, and eight millimeter(s) were used.

calculations assume a symmetric flow pattern about the disk axis, which would only be approximately true for the case of a cantilever corona electrode. However, experimentally it was shown that due to the electrical and fluidic impact of the entire cantilever structure, the air jet is angled out from the corona tip, rather than pointed directly down at the substrate. This creates a cooling zone area that is approximately circular and positioned out in front of the cantilever as shown in Figure 10, making the disk assumption a fair approximation.

The EFA thermal cooling efficiency can be calculated by dividing the thermal power removed by the EFA device over a given area by the total power input to the system by EFA operation. The calculation was done over the same four discs described in the convective heat transfer coefficient, and their thermal cooling efficiency percent are shown in Figure 9. Cooling efficiency ranged from 3.27×10^5 % to 133 %, decreasing with decreasing thermal exchange area and increasing applied voltage V_e . Although the velocity and convective heat transfer coefficient increase linearly with increasing voltage, the EFA current and thus power increase exponentially with the increasing voltage, giving the highest airflow and cooling efficiencies at the lowest operating voltages. Notably, heat generation from the corona discharge was taken into account in this analysis by applying a constant temperature to the corona electrode tip that was two degrees higher than ambient, which was the largest temperature rise seen on the corona electrode from experimental analysis with IR imaging. However, heat generation will occur throughout the ionization zone and from ion bombardment on the substrate that was not modeled in this investigation that would decrease the convection heat transfer coefficients and cooling efficiency values presented here. These heating effects are likely only to have a significant effect when the EFA is operating at the edge of its breakdown electric potential.

VI. Experimental Results

A meso-scale cantilever EFA shown in Figure 2 was microfabricated in silicon and examined for proof of concept EFA-enhanced convection cooling. Figure 3(a) shows schematically the cross-section of the experimental setup, where the ion collection and heat transfer surface includes a five millimeter thick layer of conductive foam on top of a hot plate. Conductive foam was chosen due to its non-reflective property making it a good candidate for IR imaging. The insulating layer above the collector electrode was a four-millimeter-thick slab of high density insulating foam. The corona electrode, located on top of the insulating foam, was a cantilever beam protruding over the heated surface, and connected to a portion of a silicon substrate. High voltage difference was applied between the corona and the collector electrode. Figure 10 shows four stages of the experiment. All images were taken with a FLIR ThermCAM S series camera at approximately 200 frames per second at a resolution of 230x320. The scale on the right of each image shows temperature in °C and a corresponding color (shade in the black and white version). Orange color (lighter shade in b/w) corresponds to high temperatures, and blue color (darker shade in b/w) corresponds to low temperatures. The orange (light) rectangular object at the bottom is the heated collector electrode, an equivalent of a thermal exchange surface. The blue (dark) object above it is a piece of a silicon wafer from which the cantilever corona electrode is protruding. The corona electrode is small and near ambient temperature, and therefore cannot be seen at this resolution. The position of the corona electrode can be inferred from the figures that show cooling effect. The silicon wafer is connected to the power source with a standard alligator clip. The outline of the alligator clip can be seen by looking closely above and to the right of the silicon wafer in every image. Figure 10 (a) shows the setup with a hot plate on and in steady-state regime, and with the EFA turned off. Figure 10 (b) shows how the spot directly under the corona electrode cools off slightly when the EFA is partially on (voltage is below nominal). Figure 10 (c) shows the maximum cooling effect for this setup, under nominal voltage. Figure 10 (d) is taken at the end of experiment, when the EFA was turned off and the heat distribution returned to steady-state. This experiment demonstrates that even an unoptimized setup can produce a significant cooling effect. Design, fabrication, and testing details are discussed in this reference.²²

Figure 10. Experimental demonstration of cooling effect with a micro-fabricated EFA. (a) Heated surface, EFA off, (b) $V_e = 5$ kV, $T = 10$ °C, (c) $V_e = 8.5$ kV, $T = 25$ °C, (d) re-heated surface, EFA off.

VII. Conclusions and Future Work

This paper presents a numerical coupled-physics modeling approach for electrostatic fluid accelerators (EFA) for forced convection cooling that includes space charge generation and took into account the effects of fluid dynamics and space charge diffusion. A cantilever EFA structure was analyzed using the coupled physics modeling approach, and preliminary experimental results of a cantilever EFA device microfabricated in silicon were presented. Numerical simulation results agreed well with experimental results presented in literature for EFA performance characteristics including IV characteristic trends, velocity magnitude values, velocity vs. operating voltage trends, and cooling efficiency vs. operating voltage. Average simulated EFA air jet velocities ranged from 1 m/s to 7.6 m/s over a one millimeter cross-section. Maximum convection heat transfer coefficient was found to be 282 W/(m²K) over a disk-shaped surface area with a radius of one millimeter. Proof of concept microfabricated EFA forced convection cooling device demonstrated a 25° surface temperature reduction while operating. Future work will incorporate space charge generation modeling with field emission for micro- and nano-scale emitters, as well as models with geometries optimized for heat transfer.

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