MODELING DBD-PLASMA SURFACE INTERACTIONS

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DBDs INTERACTING WITH SURFACES

- DBDs interact with surfaces through plasma induced chemistry, sub-surface electric fields and kinetics energy of ions – how important are these interactions to actuators? Examples from our work.....

- Treating human tissue - multiple filaments

- Functionalization of polymer beads.

- Polymer treatment

Thumb (floating electrode)
MODELING PLATFORM: *nonPDPSIM*

- Charges: Poisson’s & continuity equations (with surface charge) simultaneously solved using a Newton iteration technique.

\[ - \nabla \cdot \varepsilon \nabla \Phi = \sum_j N_j q_j + \rho_s \quad \frac{\partial N_j}{\partial t} = -\nabla \cdot \phi_j + S_j \]

\[ \frac{\partial \rho_s}{\partial t} = \sum_j -q_j (\nabla \cdot \phi_j + S_j) - \nabla \cdot (\sigma(-\nabla \Phi)) \]

- Electron energy equation

\[ \frac{\partial (n_e \varepsilon)}{\partial t} = j \cdot \vec{E} - n_e \sum_i N_i \kappa_i - \nabla \cdot \left( \frac{5}{2} \varepsilon \varphi - \lambda \nabla T_e \right), \quad j = q \phi_e \]

- Radiation transport and photoionization.

\[ S_m(\vec{r}) = N_m(\vec{r}) \cdot \sum_k \sigma_{mk} A_k \int N_k(\vec{r}_j') G_k(\vec{r}_j', \vec{r}_i) d^3 r_j' \]

\[ G(\vec{r}_j', \vec{r}_i) = \exp \left( - \sum_l \sigma_{ll} N_l(\vec{r}_j') d \vec{r}_j' \right) \]

\[ \frac{4\pi |\vec{r}_j' - \vec{r}_i|^2}{4\pi |\vec{r}_j' - \vec{r}_i|^2} \]

- Neutrals: Unsteady compressible fluid averaged mass, momentum, energy.

\[ \frac{\partial \rho}{\partial t} = -\nabla \cdot (\rho \vec{v}) + (\text{inlets, pumps}) \]

\[ \frac{\partial (\rho \vec{v})}{\partial t} = -\nabla (NkT) - \nabla \cdot (\rho \vec{v} \vec{v}) - \nabla \cdot \vec{\mu} + \sum q_i N_i \vec{E}_i + \sum \rho (\vec{v}_j - v) \nu_j \]

\[ \frac{\partial (\rho c_p T)}{\partial t} = -\nabla \left( -k \nabla T + \rho \vec{v} c_p T \right) + P_i \nabla \cdot v_f - \sum_i R_i \Delta H_i + \sum j \vec{j}_i \cdot \vec{E} \]

- Coupling between charged and neutral species via collisional terms in momentum, energy.

- IEADs to surfaces from Monte Carlo simulation.

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The properties of streamers are affected by small objects they intersect.

More diffusive and wider negative streamer.

In actuators, dust particles can produce pulse-to-pulse variability in DBD properties.

Humid air: \( \text{N}_2/\text{O}_2/\text{H}_2\text{O} = 79.5/19.5/1.0 \), Beads: 45 microns, \( \varepsilon/\varepsilon_0 = 2, 80 \)
E/N AND IEAD: $\varepsilon/\varepsilon_0$ OF PARTICLE MATTERS!

- $\varepsilon/\varepsilon_0 = 2$
- $\varepsilon/\varepsilon_0 = 80$
- $O_2^+$ Flux Lines

- Streamers interact with their environment.
- Secondary streamers are launched from underside of high $\varepsilon/\varepsilon_0$ particle due to high polarization.
- Energetic ions delivered to particle even at atmospheric pressure!

MIN  MAX

Animation Slide-GIF

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- 0-2.5 ns
IEADs (AND E-FIELDS) ONTO FLAT DIELECTRIC SURFACE

- E-field (kV/cm)
- \([\text{O}_2^+]\) (5x10^{13} \text{ cm}^{-3}, 3 \text{ dec})
- IEAD

Streamers in DDB can produce electric fields of 100s kV/cm at surface - compression of potential ahead of streamer and surface charges.

Even at atmospheric pressure, this is sufficient to produce ions up to 30 eV (or more) striking the dielectric surface.

Positive corona. \(\text{N}_2/\text{O}_2/\text{H}_2\text{O} = 79.5/19.5/1.0\)

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SINGLE FILAMENT TO DIELECTRIC (HUMAN THUMB):
FIELD, Te AND AIR CHEMISTERY MATTER

- $N_2$, $O_2$

- Full plasma chemical reaction mechanism is included in the model (25 species and 153 reactions).

- The complexity of a full air plasma reaction mechanism (e.g., $N_2^+$, $N_4^+$, $N^+$, $O_2^+$, $O^+$, $H_2O^+$, $O_2^-$, $O^-$) necessitates more computation time.

- Negative corona in humid air, 1 atm, -30 kV
MULTIPLE STREAMERS: REPELING EFFECT

- 30 kV

• The trajectories of negative (and positive?) streamers depend on their proximity to other streamers and the space charge they produce.

• For identical conditions, changing voltages changes angular impulse from streamer to air.
  • Negative corona, \( \text{N}_2/\text{O}_2/\text{H}_2\text{O} = 79.5/19.5/1.0 \)
  • 1 atm, -30 kV

- 50 kV

MIN  Log scale  MAX

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• Height 7000 ft (590 Torr, 278 K)
• $M = 0.1$ ($c_0 = 330$ m/s), $V = 6$ kV (100 MHz), Electrode thickness 0.008 cm
• Negative part of RF cycle: injecting sharp edge of exposed electrode.
- Positive part of RF cycle.

MIN

Log scale

MAX

Actuator Chemistry: Positive Part of RF Cycle

Potential ($\omega t = \pi/2$)

$3 \text{kV}$

$-3 \text{kV}$

$[e] 1.6 \times 10^{15} \text{ cm}^{-3}$ (3 dec)

$O_3 1.1 \times 10^{13} \text{ cm}^{-3}$ (3 dec)

$O 2.5 \times 10^{13} \text{ cm}^{-3}$ (3 dec)

$O_2^* 6.8 \times 10^{13} \text{ cm}^{-3}$ (3 dec)

Dielectric $\varepsilon/\varepsilon_0 = 5$

$E=1.5 \times 10^{14} \text{ V cm}^{-2}$

$\rho = 2.0 \times 10^{14} \text{ cm}^{-3}$ (2 dec)

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CHALLENGES FOR MODELING DBDs INTERACTING WITH ACTUATOR SURFACES

- Behavior of DBD streamers depend on polarity – scaling differs on positive and negative rf cycles.
- Interaction of streamers with materials strongly depend on dielectric properties and orientation.
  - Scaling of actuators to new material systems or geometries will not obey simple scaling laws. System approach is necessary.
- Streamers interact with themselves through “proximity effect”.
  - Larger density of streamers (higher power?) or higher voltage will impart quantitatively different impulse to gas.
- Large electric fields due to compression of potential while filament approaches the dielectrics produces large sheath potentials.
  - Streamers do not passively intersect surfaces – kinetics effects deliver ions up to (exceeding?) 30 eV – polarity dependent.
- And then there is chemistry....
- Predicted DBD properties depend on reaction mechanism and ambient conditions.
- Higher humidity air produces different ion composition and electric field profile (and so different momentum transfer) than dry air.
- The complexity of a full air plasma reaction mechanism (e.g., N₂⁺, N₄⁺, N⁺, O₂⁺, O⁺, H₂O⁺, O₂⁻, O⁻) necessitates more computation time.
- However, the DBD actuator at 100 ft. in the Tropics will operate different than the DBD actuator at 10,000 ft above the Arctic – and to make those predictions, full chemistry is required.

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**SINGLE FILAMENT TO DIELECTRIC (HUMAN THUMB): FIELD, Te AND AIR CHEMISTRY MATTER**

- \( N_2, O_2 \)
  
  \[
  e + N_2 \rightarrow N_2(v) + e \\
  e + N_2 \rightarrow N_2(A) + e \\
  e + N_2 \rightarrow N + N + e \\
  e + N_2 \rightarrow N_2^+ + e + e \\
  e + O_2 \rightarrow O_2(v) + e \\
  e + O_2 \rightarrow O_2( ^1\Delta ) + e \\
  e + O_2 \rightarrow O + O + e \\
  e + O_2 \rightarrow O_2^+ + e + e \\
  e + O_2 \rightarrow O^- + O \\
  e + O_2 + M \rightarrow O^- + M 
  \]

- **Efield (0-170 kV/cm)**

- **[e]x10^{13} cm^{-3} (2 dec)**

- **Te (0-8.2 eV)**

- Full plasma chemical reaction mechanism is included in the model (25 species and 153 reactions).

- Deep penetration of electric fields into dielectric human skin (0.5-1 mm), High temperature of electrons (up to 8.2 eV).

- Negative corona in air, 1 atm, -30 kV

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MULTIPLE STREAMERS: MUTUAL INTERACTIONS

- Properties of streamers depend on their proximity to other streamers – and trajectory intersecting surface.
- Example: DBD treatment of human tissue (a thumb!) in plasma medicine applications.
- DBD-thumb distance: 1 to 2.5 mm.

- Negative corona, $N_2/O_2/H_2O = 79.5/19.5/1.0$
- 1 atm, -30 kV

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