Electrically Driven Single Phase Thermal Management: STP-H5 EHD Experiment

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Technical Overview

EHD Thermal Multifunctional Plate

- Breadboard Hardware: STP-H5 Experiment
- Numerical Model
  - EHD Phenomena: Conduction Pumping
  - Design Tool
- Future Development
  - Smaller EHD Pumps
  - Higher Flow Rates
  - Intelligent Operations:
    - Variable Voltage Power Supply
    - Control System
5 parallel EHD Pumps operating at 1000 Vdc
• ~ 0.5 g/s HFE 7100
• ~1000 Pa

Instrumentation
• Thermal Mass Flow
• 7 TCs

Status
• Flight Configuration
• S/C Environmental
• Launch: Summer 2016
STP-H5 EHD Experiment: Prototype Multifunctional Plate

- Ultem Electrode Spacers
- Ultem Pump Housing
- SS EHD Electrodes
- SS Cover Plate
- Electrical Pins (Redundant)
- Inlet/Outlet Manifolds
- Inlet/Outlet Tube (welded - preferred)
EHD Based Structural-Thermal Multifunctional Plate

- Design & Fab EHD electrodes
  - Electrode Fabrication: Hi Voltage & Ground
  - Smooth Sharp Edges
  - Insulate non-active surfaces
- Integrate EHD electrodes
  - Set into Ultem Container
  - Insert Ultem Spacers
  - Apply Epoxy/Closed out Pumps
- Integrate into Multi-functional Plate
Electrohydrodynamic (EHD) Phenomenon

\[ f_e = \rho_e E - \frac{1}{2} E^2 \nabla \varepsilon + \frac{1}{2} \nabla \left[ E^2 \left( \frac{\partial \varepsilon}{\partial \rho} \right)_T \right] \rho \]

- Interaction of electric fields and free charges in a dielectric fluid
- Coulomb force main mechanism of this interaction
- Electric field and free charges required
EHD: Advantages & Constraints

Advantages

• simple design
• light weight
• non-mechanical, no rotating machinery
• rapid and easy control of performance
• low power consumption
• low acoustic noise
• smart system

Constraints

• high voltage/electric field
• electric field interference
• electrically conductive fluids
• low pumping efficiency
Molecules dissociate into positive and negative ions, while ions recombine into neutral molecules. When electrical field intensity is low, dissociation & recombination rates are in dynamic equilibrium.

High electric field intensity causes the rate of dissociation to exceed the rate of recombination.

These charges redistribute due to the electric field, forming heterocharge layers. The attraction of charges to the nearby electrode causes fluid motion. By designing electrodes to produce asymmetry of electric field, net flow results.
Experimental Work: Experimental study of EHD Conduction Pumping at the Meso- and Micro-scale

• Work done by Pearson and Yagoobi [4]

Penetrating and flush electrode designs showing heterocharge layers and arrows showing fluid flow attraction towards electrodes

First confirmation of EHD conduction-driven single-phase flow in meso- and micro-scale: experimental
EHD: Governing Equations

- Equations that govern charge density:

\[
\frac{\partial p_{eq}}{\partial t} + \nabla \cdot \Gamma_+ = k_D c - k_R p_{eq} n_{eq}
\]

\[
\frac{\partial n_{eq}}{\partial t} + \nabla \cdot \Gamma_- = k_D c - k_R p_{eq} n_{eq}
\]

\[
\Gamma_+ = b_+ p_{eq} E + p_{eq} u - D_+ \nabla p_{eq}
\]

\[
\Gamma_- = -b_- n_{eq} E + n_{eq} u - D_- \nabla n_{eq}
\]

- Electric field vector:

\[
\nabla \cdot E = \frac{\rho_e}{\varepsilon} = \frac{p_{eq} - n_{eq}}{\varepsilon}
\]

\[
E = -\nabla \phi
\]
• Electric body force density:

\[ f_e = \rho_e E - \frac{1}{2} E^2 \nabla \varepsilon + \frac{1}{2} \nabla \left[ E^2 \left( \frac{\partial \varepsilon}{\partial \rho} \right)_T \rho \right] \]

• Continuity equation:

\[ \nabla \cdot \mathbf{u} = 0 \]

• Momentum equation:

\[ \rho (\mathbf{u} \cdot \nabla) \mathbf{u} = -\nabla P + \mu \nabla^2 \mathbf{u} + \rho \mathbf{g} + \rho_e \mathbf{E} \]
EHD: Governing Equations

• Non-dimensional scaling

\[
p^* = \frac{p}{n_{eq}} \quad n^* = \frac{n}{n_{eq}} \quad E^* = \frac{E}{V/d} \quad \phi^* = \frac{\phi}{V} \\
P^* = \frac{p}{\mu^2/\rho d^2} \quad u^* = \frac{u}{bV/d}
\]

• Field-induced dissociation also introduced into equations (3) and (4) for charge conservation, become:

\[
\nabla^* \cdot (p^* (u^* + E^*) - \alpha \nabla^* p^*) = 2C_0 (F(\omega) - p^* n^*)
\]

\[
\nabla^* \cdot (n^* (u^* - E^*) - \alpha \nabla^* n^*) = 2C_0 (F(\omega) - p^* n^*)
\]

Where

\[
C_0 = \frac{n_{eq} d^2}{\varepsilon V} = \frac{\sigma d^2}{2b \varepsilon V} \quad \text{and} \quad \alpha = \frac{D}{bV} = \frac{k_B T}{eV}
\]
EHD: Governing Equations

• Equations for (7) and (8) for electrical field become:

\[ \nabla^* \cdot E^* = C_0(p^* - n^*) \quad (16) \]
\[ E^* = -\nabla^* \phi^* \quad (17) \]

• Equations (10) and (11) for continuity and momentum become:

\[ \nabla^* \cdot u^* = 0 \quad (18) \]
\[ (u^* \cdot \nabla)u^* = -\left(\frac{1}{Re_{EHD}}\right)^2 \nabla^* P^* + \frac{1}{Re_{EHD}} \nabla^* u^* + M_0^2 C_0 (p^* - n^*) \boldsymbol{E}^* \quad (19) \]

Where

\[ Re_{EHD} = \frac{\rho b V}{\mu} \quad \text{and} \quad M_0 = \sqrt{\frac{\varepsilon}{\rho b^2}} \quad (20) \]
EHD: Numerical Results – EHD Force (Preliminary)

Numerical Solution continued

• Stream traces for electric body force and contours of dimensionless electric body force magnitude
EHD: Numerical Results – Charge Distribution (Preliminary)

Numerical Solution continued

- Dimensionless net charge density distribution ($p^* - n^*$) at vicinity of two electrodes
Multi-Functional Plate: Next Generation Development Challenges

• Simplify Pump Design
  – Eliminate spacers
  – Eliminate Ultem Housing

• Power System
  – Variable voltage power source (in progress)
  – Independent Pump Operations
  – Electric Bus Design

• Higher Flow Rate Pumps
• Smaller Pumps & Channels