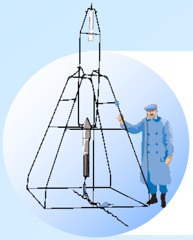


# Electrically Driven Single Phase Thermal Management: STP-H5 EHD Experiment


**Jeffrey R. Didion**

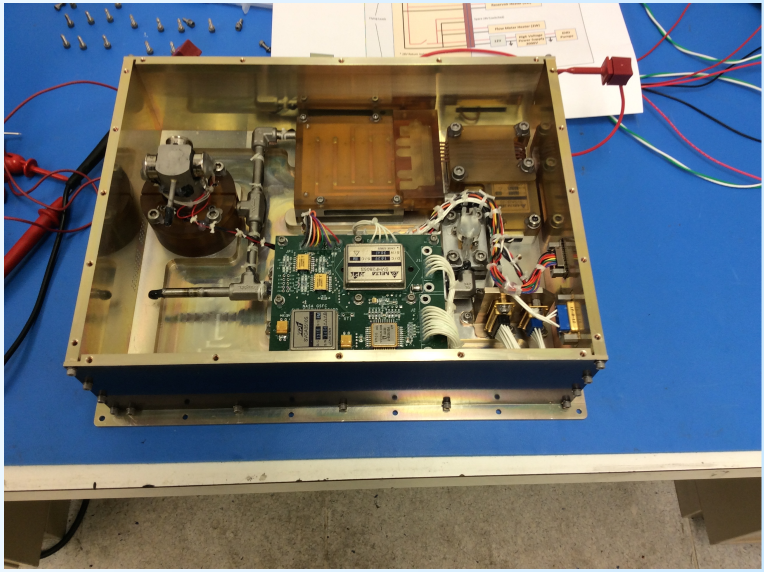
**Senior Thermal Engineer**

**Manager, Nanotechnology Facility**

# 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



# STP-H5 EHD Experiment: Proof of Concept & Life Test Loop

5 parallel EHD Pumps operating at 1000 Vdc

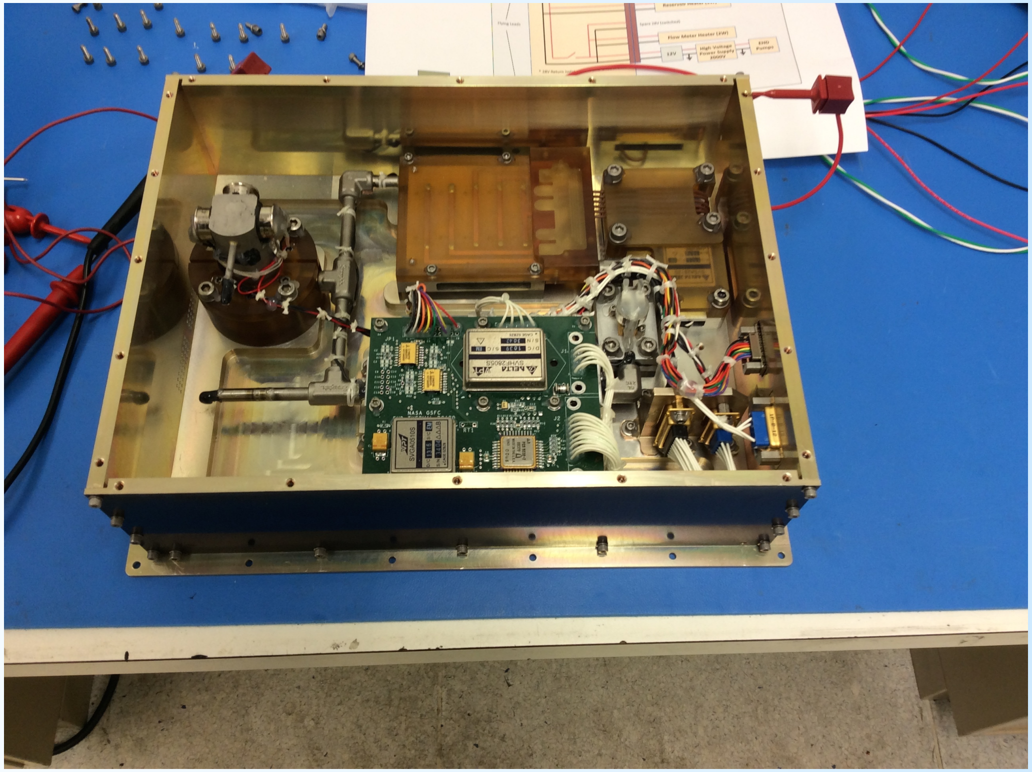
- ~ 0.5 g/s HFE 7100
- ~1000 Pa

Instrumentation

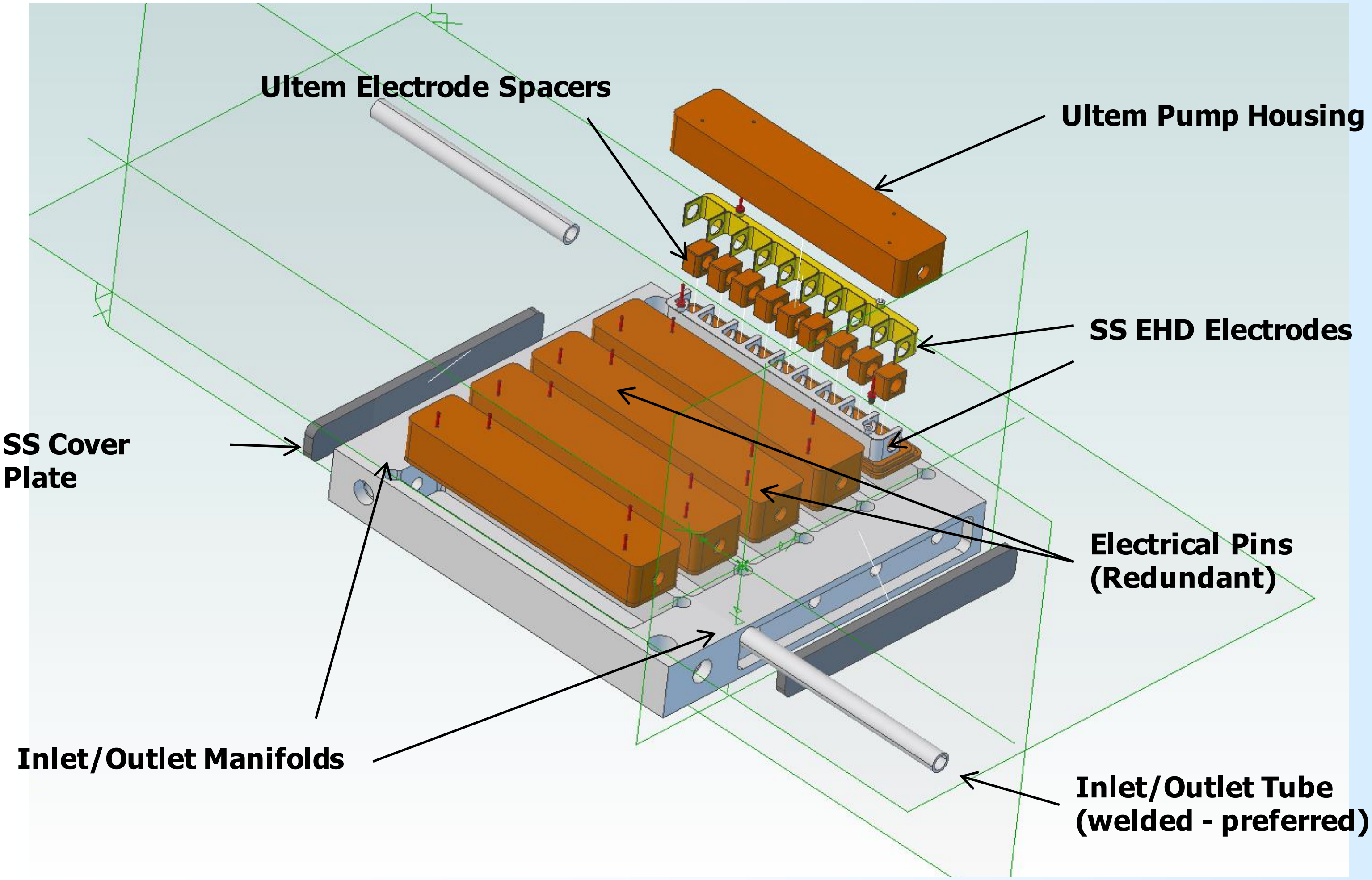
- Thermal Mass Flow
- 7 TCs

Status

- Flight Configuration
- S/C Environmental
- Launch: Summer 2016

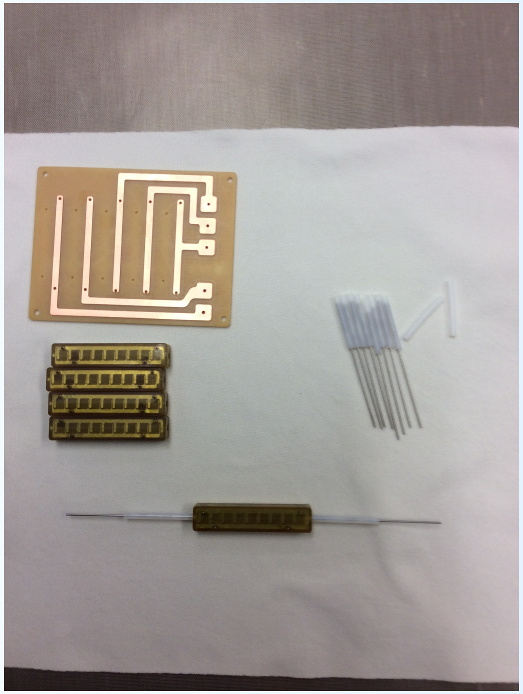


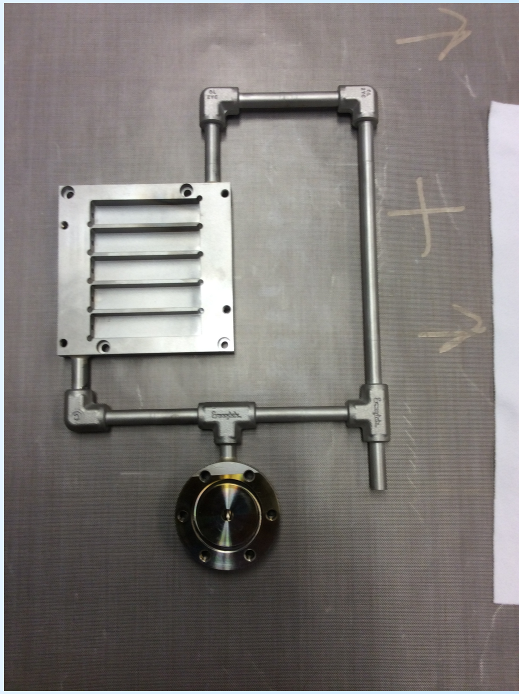
# STP-H5 EHD Experiment: Prototype Multifunctional Plate

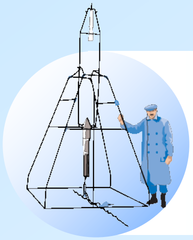


# EHD Based Structural-Thermal Multifunctional Plate

- **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**





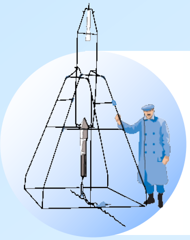


# EHD Numerical: EHD Phenomenon

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

Coulomb Force — Polarization Forces

- 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

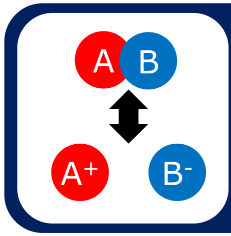
## Advantages

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

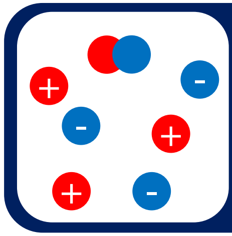
## Constraints

- high voltage/electric field
- electric field interference
- electrically conductive fluids
- low pumping efficiency

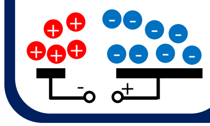
# EHD: Conduction Phenomena




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.

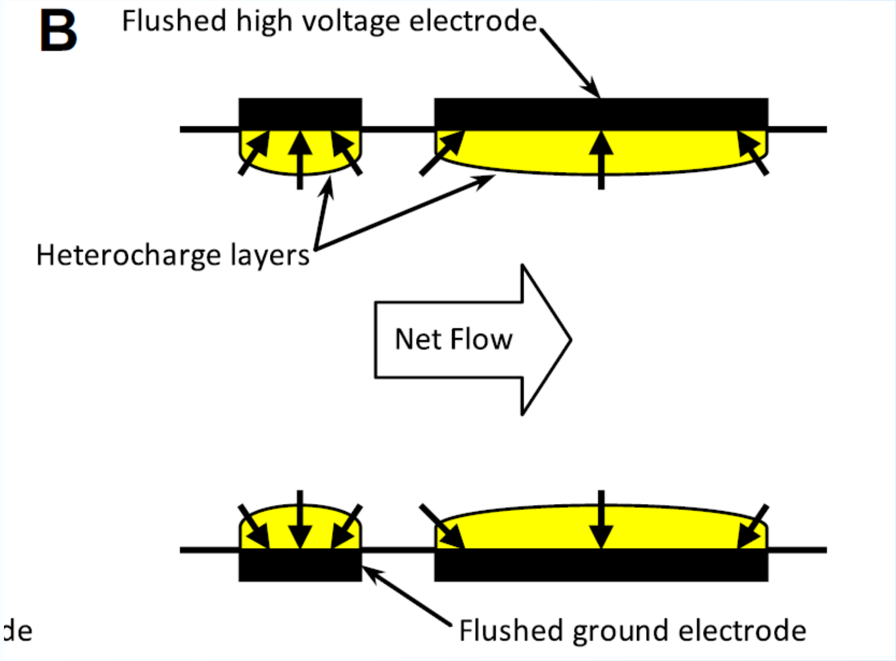


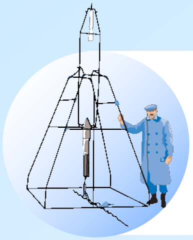
High electric field intensity causes the rate of dissociation to exceed the rate of recombination.



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.

# EHD: STP-H5 EHD Conduction Pumps





# EHD: Governing Equations

- Equations that govern charge density:

$$\frac{\partial p_{eq}}{\partial t} + \nabla \cdot \boldsymbol{\Gamma}_+ = k_D c - k_R p_{eq} n_{eq}$$

$$\frac{\partial n_{eq}}{\partial t} + \nabla \cdot \boldsymbol{\Gamma}_- = k_D c - k_R p_{eq} n_{eq}$$

$$\boldsymbol{\Gamma}_+ = b_+ p_{eq} \boldsymbol{E} + p_{eq} \boldsymbol{u} - D_+ \nabla p_{eq}$$

$$\boldsymbol{\Gamma}_- = -b_- n_{eq} \boldsymbol{E} + n_{eq} \boldsymbol{u} - D_- \nabla n_{eq}$$

- Electric field vector:

$$\nabla \cdot \boldsymbol{E} = \frac{\rho_e}{\varepsilon} = \frac{p_{eq} - n_{eq}}{\varepsilon}$$

$$\boldsymbol{E} = -\nabla \phi$$

# EHD: Governing Equations

- Electric body force density:

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

- Continuity equation:

$$\nabla \cdot \boldsymbol{u} = 0$$

- Momentum equation:

$$\rho (\boldsymbol{u} \cdot \nabla) \boldsymbol{u} = -\nabla P + \mu \nabla^2 \boldsymbol{u} + \rho \boldsymbol{g} + \rho_e \boldsymbol{E}$$

# EHD: Governing Equations

- Non-dimensional scaling

$$p^* = \frac{p}{n_{eq}} \qquad n^* = \frac{n}{n_{eq}} \qquad \boldsymbol{E}^* = \frac{\boldsymbol{E}}{V/d} \qquad \phi^* = \frac{\phi}{V}$$

$$P^* = \frac{P}{\mu^2/\rho d^2} \qquad \boldsymbol{u}^* = \frac{\boldsymbol{u}}{bV/d}$$

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

$$\nabla^* \cdot (p^*(\boldsymbol{u}^* + \boldsymbol{E}^*) - \alpha\nabla^* p^*) = 2C_0(F(\omega) - p^* n^*)$$

$$\nabla^* \cdot (n^*(\boldsymbol{u}^* - \boldsymbol{E}^*) - \alpha\nabla^* n^*) = 2C_0(F(\omega) - p^* n^*)$$

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:

$$\nabla^* \cdot \boldsymbol{E}^* = C_0(p^* - n^*) \qquad (16)$$

$$\boldsymbol{E}^* = -\nabla^* \phi^* \qquad (17)$$

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

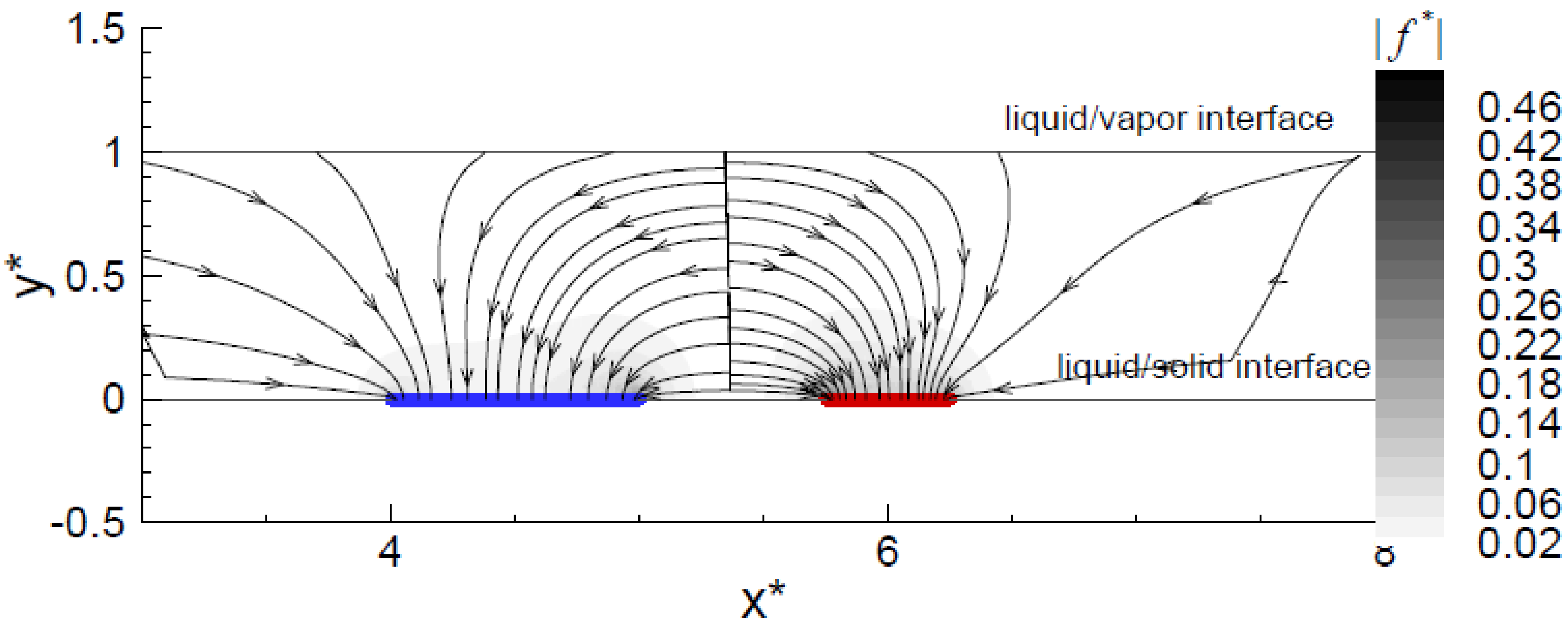
$$\nabla^* \cdot \boldsymbol{u}^* = 0 \qquad (18)$$

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

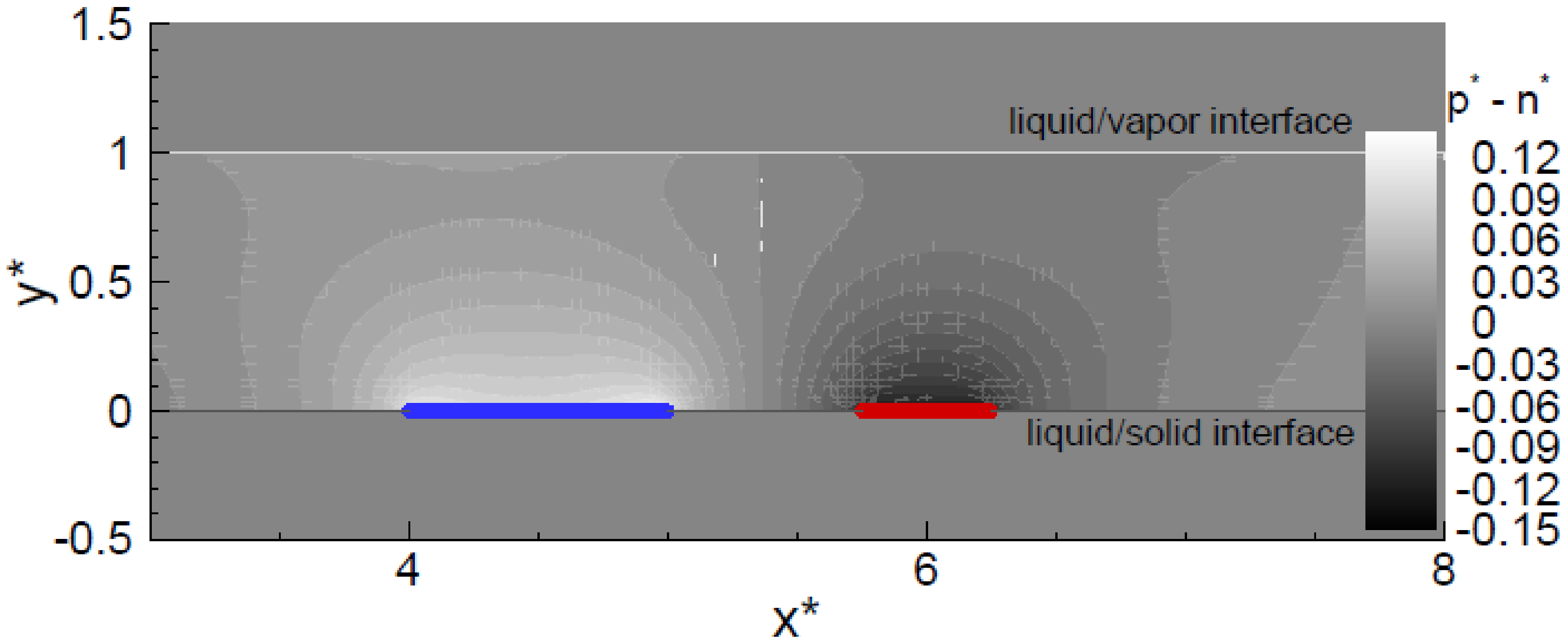
Where

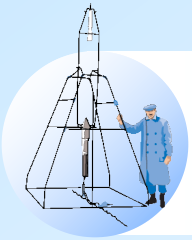
$$Re_{EHD} = \frac{\rho b V}{\mu} \quad \text{and} \quad M_0 = \sqrt{\frac{\varepsilon}{\rho b^2}} \qquad (20)$$

# EHD: Numerical Results – EHD Force (Preliminary)



# EHD: Numerical Results – Charge Distribution (Preliminary)





# 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