Electrically Driven Thermal Management: Flight Validation, Experiment Development, Future Technologies

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Technical Overview

- **STP-H5 EHD Conduction Pump Life Test & Flight Demonstration: Jeffrey Didion NASA GSFC**
  - Demonstrated Long Term EHD Liquid Pumping Capability
  - Electric Driven Convection: viable Thermal Management Technology

- **Electrically Driven Liquid Film Boiling in the Absence of Gravity: Jamal Yagoobi WPI & Jeffrey Didion**
  - Feasibility of Liquid Film Boiling in Microgravity (ISS 2021 MSG Facility)
  - Demonstrate Liquid - Vapor Fluid Management in microgravity
  - Develop Numerical Models & Design Procedures

- **Future Technologies**
  - Electrospray Joel Chapman/Andrei Fedorov Georgia Tech: NSTRF Program
  - Micro/Nano Scale Electrically Driven Flow: Michal Talmor/Jamal Yagoobi WPI: NSTRF Program
  - Oscillating Heat Pipe (OHP): Joel Chapman/Jeffrey Didion/JenTung Ku
GSFC ISEM Package: PI Thomas Flatley/GSFC
EHD Experiment: PI Jeffrey Didion
STP-H5 EHD Conduction Pump Life Test & Flight Demonstration

Experiment Significance

- Demonstrate Electrically Driven Convection as feasible technology
  - Engineering subsystems
  - Flow Control
- GSFC Manufacturing Advances
  - Higher pressure head pumps
  - Two Phase Systems (ISS FBCE Experiment Mudawar/Hasan)
- Future Technology Development
  - Higher Heat Flux Applications
  - Small Scale Applications

EHD Experiment
EHD Experiment Pump Performance

- 1000 Vdc applied
- Intermittent Operation at ISEM discretion
- Consistent Operation: no apparent fluid degradation
EHD Experiment Loop Set Point

- Two Phase Reservoir: HFE7100 Working Fluid
- Thermal Controller
EHD Conduction Pumping

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.
Higher Pressure EHD Conduction Pumps

EHD Conduction Phenomena

- Geometry Dependent
- Advanced Manufacturing Techniques: Smaller Size & Lower Applied Voltage
**Objective:**
- Characterize the effects of gravity on the interaction of electric and flow fields in the presence of phase change specifically pertaining to:
  - The effects of microgravity on the electrically generated two-phase flow.
  - The effects of microgravity on electrically driven liquid film boiling (includes extreme heat fluxes).
- Electro-wetting of the boiling section will repel the bubbles away from the heated surface in microgravity environment.

**Relevance/Impact:**
- Provides phenomenological foundation for the development of electric field based two-phase thermal management systems leveraging EHD, permitting optimization of heat transfer surface area to volume ratios as well as achievement of high heat transfer coefficients thus resulting in system mass and volume savings.
- EHD replaces buoyancy or flow driven bubble removal from heated surface.

**Development Approach:**
- Conduct preliminary experiments in low gravity and ground-based facilities to refine technique and obtain preliminary data for model development.
- ISS environment required to characterize electro-wetting effect on nucleate boiling and CHF in the absence of gravity.
- Microgravity Science Glovebox (MSG – 2021)
Objective:

- Investigate combined effect of Dielectrophoretic Force and Electrophoretic Force (Conduction Mechanism) on heat transfer enhancement

\[ F_{DEP} = 2\pi a^3 \varepsilon_1 \left( \frac{\varepsilon_2 - \varepsilon_1}{\varepsilon_2 + 2\varepsilon_1} \right) \nabla |E_e|^2 \]
The dielectrophoretic force is proportional to the gradient of the electric field, \( \frac{\partial \varepsilon}{\partial \rho} \) and its permittivity is found in \( \varepsilon_2 \). Therefore, the DEP force acting on a given vapor bubble is given by:

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

where:
- \( f_e \) is the electric field force
- \( \rho_e \) is the electric charge density
- \( E \) is the electric field
- \( \varepsilon \) is the permittivity
- \( \nabla \) is the gradient operator
- \( T \) is the temperature

**Coulomb Force**

**Polarization Forces**

The DEP force is greater than the buoyancy force acting on a vapor bubble, which is less than that of a suspension medium.

\[
\varepsilon_2 < \varepsilon_1 < \varepsilon_0
\]

\[
\varepsilon = \frac{\varepsilon_2 - \varepsilon_1}{\varepsilon_2 + 2\varepsilon_1}
\]

\[
\nabla|E_e|^2
\]

**Di-Electrophoretic Force**

Di-Electrophoretic Force enables and enhances liquid film boiling.
Electrically Driven Liquid Film Boiling Experiment: Hardware Development

Science Validation Loop
Electrified Liquid Jets for Evaporative Heat Transfer Enhancement

Joel Chapman, Peter Kottke, Andrei Fedorov

This work was supported by NASA Space Technology Research Fellowship, Project Number NNX16AM95H.
Charged ions are forced out of the capillary opening by the electric field, shaping the liquid into a cone (known as a Taylor Cone) at the tip.

- Cone becomes unstable and produces a narrow spray jet.
- Due to Coulombic repulsion between the charged ions, the jet spreads and breaks into a plume of nano-scale droplets.
- Electric field drives droplets to counter-electrode.

Effect of electrospray potential on spray geometry

1000 nL/min spray flow of DI water with 0.1% acetic acid dopant through a 3.25 µm ID fused silica capillary at spray voltages noted above. Small blue/red reference lines shown near the capillary tip in each photo are approximately 24µm long. Images taken at 1000x using Keyence 500f microscope. Spray plume illuminated using a laser. The counter electrode was Indium Tin Oxide (ITO)-coated polished float glass placed approximately 2mm from the capillary tip.
Liquid Impinging on Indium Tin Oxide Test Device for Film Visualization Experiments

Reducing actively heated ITO area limits resistive heat production to area under spray (1.4 x 1.4 mm)
ES Impingement Permits Film Shape Control

Dome
Low ES voltage or distant spray.

- Creating thin films using electrospray impingement reduces conduction resistance.
- Modeling predicts significant thermal performance improvement by impingement-flattening.

Torus
High ES voltage, spray source near substrate.

Thin Film
Significant thinning of film under the impingement site for high ES voltage. Color banding is due to light interference patterns, not post-processing. Films seen here less than 350nm thick.
Microfabricated Test Devices, Experiments

- Experiments on microfabricated test devices corroborate the hypothesis that high-ES impingement yields greatly improved evaporative heat transfer enhancement.
- Using methanol as ES working fluid, dissipated 245 W/cm² from <100°C hotspot.

Microfabricated 16-RTD array at 100x
Recipient: Michal (Michelle) Talmor, Advisor: Jamal Yagoobi

- Goal of NSTRF Project:
  - Study flow distribution control behavior and smart, active heat transfer enhancement utilizing Electrohydrodynamic (EHD) conduction pumps at multiple size scales, in single and two-phase flows
  - Study the underlying electrochemical charge formation processes present in EHD conduction pumping, and how they are affected by pumping orientations and externally applied loads
  - Obtain fundamental understand the effect of temperature on the EHD conduction pumping mechanism
  - Obtain scaling laws and recommended design practices for EHD conduction driven flow distribution systems at different size scales, for different operational conditions
Theoretical Work: Simulated Heterocharge Layer Morphology

- Externally applied flow
- Two electrode pairs
- Max. voltage of 1500V

**In forward orientation:**
- EHD pump is parallel to the main flow
- Diminishing layer height on subsequent electrode pairs
- Eroded layer heights with higher incoming flow velocity

**In reversed configuration:**
- EHD pump is acting against the main flow
- Increasing layer height on subsequent electrode pairs
- Increased layer heights with higher incoming flow velocity

(white layers over ground electrodes, black layers over high voltage electrodes)
Collaboration with the University of Poitiers, France
Particle Imaging Velocimetry flow field measurements using unique PTFE particles
Multiple pairs of EHD conduction electrodes, activated at 0-18kV
Closed and open loop
With and without externally applied flow via mechanical pump

PIV Flow Visualization of EHD Conduction
Oscillating Heat Pipe Project

Swagelok purge and fill valves

Condenser Coldplate Clamshell

“Adiabatic” Section – Under view of thermal imaging Camera

Heat applied by running current through resistive wire-wraps
Experiment Set Up

- Chill water
- Insulate
- Not Insulated
- Insulate

Data acquisition for Thermocouples

Thermal Imaging of Adiabatic Section
Investigation Goals

• Analyze Adiabatic ‘Springs’
• Analyze Forces in Turns
• Evaluate Differential Heating, i.e., non-uniform heating in evaporator section