Electrically Driven Liquid Film Boiling Experiment

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ElectroHydroDynamic (EHD) Physics

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

- Coulomb Force
- Polarization Forces

Electrophoretic Force (Coulomb): Liquid Pumping
Dielectrophoretic (Polarization): Two Phase Management
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.
Electrophoretic Pumping: Channel

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
Di-electrophoretic Phase Management

Figure 27: Electrophoresis and dielectrophoresis in uniform and non-uniform DC electric field

Figure 28: Electrophoresis and dielectrophoresis in non-uniform AC electric field

Figure 3. Dielectrophoretic Force in Uniform and Non-Uniform Field

\[ F_{DEP} = 2\pi a^3 \varepsilon_1 \left( \frac{\varepsilon_2 - \varepsilon_1}{\varepsilon_2 + 2\varepsilon_1} \right) \nabla |E_e|^2 \]
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.
- Will operate in the FIR – designed for autonomous operation.
Objective:

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

\[ F_{DEP} = 2\pi a^3 \varepsilon_1 \left( \frac{\varepsilon_2 - \varepsilon_1}{\varepsilon_2 + 2\varepsilon_1} \right) V|E_c|^2 \]
Application: High Heat Flux High Temperature Heat Acquisition

- NASA Space Technology Roadmaps:
  - TA 5: Communications, Navigation, and Orbital Debris Tracking and Characterization Systems
    - TA 5.5.2 Power Efficient Technologies (Ka Band amplifiers)
    - TA 5.2.6: Antennas (Ka Band Phased Arrays)
    - TA 5.5: Integrated Technologies – Radio Systems (reduced SWaP)
  - TA 14: Thermal Management Systems
    - TA 14.2.1: High Heat Flux Acquisition @ constant Temperature
    - TA 14.2.2: Advanced Efficient Pump Techniques; specifically calls out EHD pumping

- Decadal Survey Missions

  High Power RF Amplifiers (HPA) have thermal challenges that limit microwave (communication and radar) performance
  - Aerosol, Cloud and Ecosystem (ACE)
  - Snow and Cold Land Processes (SCLP)
High Temperature Heat Acquisition Advantages

- Component Heat Acquisition
- Hybrid Chip System Operation:
  - Heat Acquisition at Silicon Chip
  - Thin Film Evaporation
  - Electric Field Fluid Management
- Heat Rejection @ Lowest Temperature Sink

Radiator Size & Mass Advantage:
- Higher Heat Rejection Temperature
- Lower System Thermal Resistance

Higher Heat Rejection Temperature
Lower System Thermal Resistance

Graph showing:
- \( q_{\text{flux}} \) vs. \( T_{\text{rad}} \)
- \( \epsilon = 0.9 \)
- \( T_{\text{space}} = 100 \text{ K} \)
- State-of-the-Art
- Goal
GaN Heat Acquisition Concept

GaN Substrate Electric Field (EHD) Driven High Heat Flux
High Temperature Heat Acquisition Device

- GaN Device
- Heat Spreader (Material TBD)
- EHD Based Heat Acquisition

**Figure 3.** Approximate configuration of thermal and electrical demonstration vehicles (TDV and EDV). On the TDV, heat sources are simulated with resistive heater elements. On the EDV, the HEMT transistor junctions are the heat source.

Each will contain high-aspect microchannels on the order of 50 µm wide running through the substrate as shown in Fig. 3. Initial TDV modeling and testing will focus on an assortment of 200 × 200 µm hot spots dissipating up to 5 kW/cm². This subscale experiment will allow for a focused study of EHD conduction mechanism for flow distribution control. It will also allow for fabrication methodologies to be fine-tuned. The focus will then shift to a larger heat source (proposed size: a square with each side 2 – 4 mm, representative of a GaN or SiC IGBT die) dissipating up to 1 kW/cm², with the 200 × 200 µm hot spot at the center of the die dissipating 5 kW/cm² as shown in Fig. 3. This will require elongating the channels by at least an order of magnitude, which will in turn necessitate re-optimization of the channel geometry and electrode configuration. A third study will include a moving hot spot to study the role of EHD-controlled flow distribution through the parallel channels under changing heat local heat loads. EHD conduction phenomenon is well-suited to microscale systems, because at such scales a significant electric field (such as 75% of the dielectric strength of the fluid) can be applied with only modest voltages on the order of a few hundred volts and negligible current on the order of microamps.

The team has extensive, pre-existing modeling capability for both (1) the EHD conduction pumping phenomenon and (2) device thermal design optimization. These capabilities will be leveraged to optimize the design and placement of the EHD electrodes to maximize the supplemental pressure head that they generate and ensure that there is no negative interactions between the operation of the EHD microvalves and the transistor circuitry.

Dr. Yagoobi’s research team at WPI (and previously at Texas A&M University and Illinois Institute of Technology) has developed theoretical/numerical models/codes for the EHD conduction driven fluid flow with and without phase change, in the presence and absence of gravity in micro, G

- Background heat flux (1 kW/cm²)
- Hot-spot heat flux (5 kW/cm²)
- Electrode pairs forming EHD microvalves for flow control

**Diagrams:**
- GaN MMIC layer
- SiC or Si substrate layer