Micro- and Nano-Scale Electrically Driven Two-Phase Thermal Management

Jeffrey R. Didion
Senior Thermal Engineer
Manager, Nanotechnology Facility
Technical Overview

- Fundamental Research:
  - Electrically Driven Liquid Film Boiling NASA HQ SLPSRA Division NNX12AR32G (Yagoobi/WPI & Didion)
  - Self-Sensing Thermal Management Using nano-enhanced Polymers NSTRF FY13 (Bruck & Sauerbrunn/UMD & Didion)

- Flight Hardware: Electrically Driven Liquid Film Boiling
  - ISS Fluids Rack – FY21
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.
EHD Thin Film Boiling Experiment: Combined Di-electrophoretic & Conduction Pumping

Objective:

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

\[ F_{DEP} = 2\pi a^3 \varepsilon_1 \left( \frac{\varepsilon_2 - \varepsilon_1}{\varepsilon_2 + 2\varepsilon_1} \right) V |E_e|^2 \]

Objective:

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

Heat flux, \( q'' \) (W/cm²)

Heat flux, \( q'' \) (W/cm²)

Heat flux, \( q'' \) (W/cm²)

Heat flux, \( q'' \) (W/cm²)

Heat flux, \( q'' \) (W/cm²)

Heat flux, \( q'' \) (W/cm²)

Heat flux, \( q'' \) (W/cm²)

Heat flux, \( q'' \) (W/cm²)

Heat flux, \( q'' \) (W/cm²)

Heat flux, \( q'' \) (W/cm²)

Heat flux, \( q'' \) (W/cm²)

Heat flux, \( q'' \) (W/cm²)

Heat flux, \( q'' \) (W/cm²)

Heat flux, \( q'' \) (W/cm²)

Heat flux, \( q'' \) (W/cm²)

Heat flux, \( q'' \) (W/cm²)

Heat flux, \( q'' \) (W/cm²)

Heat flux, \( q'' \) (W/cm²)

Heat flux, \( q'' \) (W/cm²)

Heat flux, \( q'' \) (W/cm²)

Heat flux, \( q'' \) (W/cm²)

Heat flux, \( q'' \) (W/cm²)

Heat flux, \( q'' \) (W/cm²)

Heat flux, \( q'' \) (W/cm²)

Heat flux, \( q'' \) (W/cm²)

Heat flux, \( q'' \) (W/cm²)

Heat flux, \( q'' \) (W/cm²)

Heat flux, \( q'' \) (W/cm²)

Heat flux, \( q'' \) (W/cm²)

Heat flux, \( q'' \) (W/cm²)

Heat flux, \( q'' \) (W/cm²)

Heat flux, \( q'' \) (W/cm²)

Heat flux, \( q'' \) (W/cm²)

Heat flux, \( q'' \) (W/cm²)

Heat flux, \( q'' \) (W/cm²)

Heat flux, \( q'' \) (W/cm²)

Heat flux, \( q'' \) (W/cm²)

Heat flux, \( q'' \) (W/cm²)

Heat flux, \( q'' \) (W/cm²)

Heat flux, \( q'' \) (W/cm²)

Heat flux, \( q'' \) (W/cm²)

Heat flux, \( q'' \) (W/cm²)

Heat flux, \( q'' \) (W/cm²)

Heat flux, \( q'' \) (W/cm²)

Heat flux, \( q'' \) (W/cm²)

Heat flux, \( q'' \) (W/cm²)

Heat flux, \( q'' \) (W/cm²)

Heat flux, \( q'' \) (W/cm²)

Heat flux, \( q'' \) (W/cm²)

Heat flux, \( q'' \) (W/cm²)

Heat flux, \( q'' \) (W/cm²)

Heat flux, \( q'' \) (W/cm²)

Heat flux, \( q'' \) (W/cm²)

Heat flux, \( q'' \) (W/cm²)

Heat flux, \( q'' \) (W/cm²)

Heat flux, \( q'' \) (W/cm²)

Heat flux, \( q'' \) (W/cm²)

Heat flux, \( q'' \) (W/cm²)

Heat flux, \( q'' \) (W/cm²)

Heat flux, \( q'' \) (W/cm²)

Heat flux, \( q'' \) (W/cm²)

Heat flux, \( q'' \) (W/cm²)

Heat flux, \( q'' \) (W/cm²)

Heat flux, \( q'' \) (W/cm²)

Heat flux, \( q'' \) (W/cm²)

Heat flux, \( q'' \) (W/cm²)

Heat flux, \( q'' \) (W/cm²)

Heat flux, \( q'' \) (W/cm²)

Heat flux, \( q'' \) (W/cm²)

Heat flux, \( q'' \) (W/cm²)

Heat flux, \( q'' \) (W/cm²)

Heat flux, \( q'' \) (W/cm²)

Heat flux, \( q'' \) (W/cm²)

Heat flux, \( q'' \) (W/cm²)

Heat flux, \( q'' \) (W/cm²)

Heat flux, \( q'' \) (W/cm²)

Heat flux, \( q'' \) (W/cm²)

Heat flux, \( q'' \) (W/cm²)

Heat flux, \( q'' \) (W/cm²)

Heat flux, \( q'' \) (W/cm²)

Heat flux, \( q'' \) (W/cm²)

Heat flux, \( q'' \) (W/cm²)

Heat flux, \( q'' \) (W/cm²)

Heat flux, \( q'' \) (W/cm²)

Heat flux, \( q'' \) (W/cm²)

Heat flux, \( q'' \) (W/cm²)

Heat flux, \( q'' \) (W/cm²)

Heat flux, \( q'' \) (W/cm²)

Heat flux, \( q'' \) (W/cm²)

Heat flux, \( q'' \) (W/cm²)

Heat flux, \( q'' \) (W/cm²)

Heat flux, \( q'' \) (W/cm²)

Heat flux, \( q'' \) (W/cm²)

Heat flux, \( q'' \) (W/cm²)

Heat flux, \( q'' \) (W/cm²)

Heat flux, \( q'' \) (W/cm²)

Heat flux, \( q'' \) (W/cm²)

Heat flux, \( q'' \) (W/cm²)

Heat flux, \( q'' \) (W/cm²)

Heat flux, \( q'' \) (W/cm²)
Meso-Scale Flow Distribution (NSTRF)

- Single and two-Phase flow
- Three parallel branches
- Entirely EHD driven
  - Branch embedded pumps
  - Flow supply pump
- Flow regime influence
- Flow distribution
  - Flow redirection
  - Maldistribution correction
  - Two-phase distribution stabilization
Micro-Scale EHD Enhanced Evaporation (NSTRF)

- Feasibility of embedded EHD enhancement
- Characterization of micro-scale perforations
  - Pressure generation
  - Flow rate generation
  - Flow regime estimate
  - Dry-out conditions
- Heat exchange loop
- Three electrode pairs
  - Two assisting upstream
  - One embedded in evaporator
**GOAL / EXPECTED OUTCOMES**
- Study flow distribution control behavior utilizing Electrohydrodynamic (EHD) conduction pumps at multiple size scales
- Study the effectiveness of EHD flow distribution systems for heat transfer using single and two-phase flows at different scales
- Obtain fundamental understanding of EHD conduction flow distribution behavior at small scales and model it mathematically
- Obtain best design practices for EHD conduction driven flow distribution systems at different scales

**TECHNICAL APPROACH**
- Initially meso-scale EHD conduction driven flow distribution experiments for both single and two-phase flows, to be scaled down in future
- Micro-scale EHD pump embedded in an evaporator for two-phase flow enhancement options
- Mathematical modeling of the fundamental physics and chemistry at micro and nano scales
- COMSOL Multiphysics software for numerical simulations

**RELEVANCE TO NASA**
- Research into Advanced Pumps, under the Heat Transfer and Thermal Control Systems TABS elements (14.2.2.2.3)
- EHD pumps have no moving parts, no fluid degradation, simple designs
- EHD conduction pumping is operational in zero gravity, with a TRL of 5 for the basic mechanism
- Possible usage in multi-purpose structural/thermal panels and in embedded electronics cooling for space applications

---

**MAJOR ACCOMPLISHMENTS (TO-DATE)**
- Meso-scale, single phase EHD conduction driven flow distribution experiments & numerical simulations based on performance information
- Partially completed meso-scale, two-phase EHD conduction driven flow distribution experiments
- Numerical COMSOL simulation of single phase EHD conduction using the macro-scale coupled electrostatic, chemical and fluid equations
- Fundamental explanation of temperature dependence of EHD conduction pressure generation performance
- Design and partial manufacturing of a micro-scale evaporator-embedded EHD pump and experimental loop for two-phase flow
- Design draft of a CubeSat structural panel with embedded distributive flow control using EHD conduction pumps
Nano-Scale Feasibility & Numerical Study (NSTRF)

- Modeling & simulation:
  - Electric double layer vs. heterocharge layers
  - Significant effects from the zeta potential
  - Capillary and electrophoresis effects
  - Dimensions and materials revisit

- Experimentation:
  - Lithographic printing
  - Flow visualization
  - Single channel
  - Flow distribution

[Diagram showing EDL and Heterocharge Layers]
Multifunctional Nano-enhanced Structure acts as 'nervous system' to map temperature distribution

Temperature Step Function Response on Invar

5 mHz Sine Wave Response on Invar
Component high heat flux embedded heat acquisition is high impact, unique technology enabling next generation of thermally limited, NASA and commercial computing, power and multifunctional platforms

- CI-TMS is innovative and unique
  - Chip Embedded Hybrid EHD/capillary device provides high heat flux acquisition at heat source
  - Thin Film Evaporation and High Heat Rejection Temperature enable SWaP-C advantages
- Spaceflight Validation of Technology Concept on CubeSat Platform

CI-TMS Proof of Concept Heat Acquisition Hardware
Component High Temperature Heat Acquisition Advantages

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 heat flux vs. temperature](image)
Silicon Based Concepts

- **Chip Integrated Component: High Temperature Heat Acquisition & Transport**
  - Thin Film evaporation for high heat acquisition rates @ low temperature difference
  - Hybrid EHD/Capillary Fluid Management

- **Silicon Manifolds Operations**
  - Liquid (blue) to heat acquisition site
  - Vapor (red) transported to heat rejection site
  - Manifold channels ~ 100 microns (gravity independence & micro-scale applications)
  - Electrohydrodynamic enhanced: alleviate dry-out; insure gravity insensitivity

- **Technologies to Enable the Concept**
  - Capillary driven flow: self regulation of mass flow rate
  - Electrohydrodynamics (EHD): fluid management (liquid/vapor control), pump enhancement
  - DRIE to manufacture micro-channels

- **Feasibility**
  - Micro-scale capillary performance demonstrated
  - EHD micro-scale microgravity fluid management in micro-gravity campaigns (May 2012 & September 2013)
  - Manufactured Proof-of-Concept micro-channel EHD electrode system
  - Manufactured Capillary Proof of Concept hardware
Silicon Based Concepts: EHD Based Thermal Management of Hot Spots

Figure 3. Approximate configuration of thermal and electrical demonstration vehicles (TDV and EDV). On the TDV, heat sources are simulated with resistive heat elements. On the EDV, the HEMT transistor junctions are the heat source. The TDV and EDV will have approximately equal overall dimensions, approximately 1–2 mm. 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,

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

GaN MMIC layer
SiC or Si substrate layer
Electrohydrodynamic (EHD) Conduction mechanism to actively distribute fluid flow in micro-channels to local hot spots

• Technical Milestones:
  – Demonstrate Ultra High High Heat Flux Thermal Management:
    • 1 kW/cm² in background
    • 5 kW/cm² at local hot spots
  – Technically Relevant Issue
    • Commercial Applications:
      – Teledyne Scientific Corp: RF amplifiers
      – UTC: power electronics

• USAF Space Vehicles; CITMAV Consortium
Technology Development Plan: Operational Approach

**Example 1**
Increase flow to channel 1 due to temporary hot-spot in that region.

**Example 2**
Overcome maldistribution by delivering supplemental pressure head to channel 2, restoring flow through that channel.

Channel Pressure Drop
- geometry
- mass flux
- heat flux

EHD Pressure Head must be of same order as channel Pressure drop to be effective.
NASA Relevance

- 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
    - TA14.2.2: 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)
Integrated Radar Subsystem ACE & SCLP: Dr. Paul Racette GSFC

- High Power Amplifiers (HPA) performance is thermally limited; Improved thermal management for GaN based amplifiers will achieve higher instrument sensitivity via higher duty cycle.
- Improved thermal management of high power RF signals alleviates the current frequency limitations (set by International Agreement) and enable the development of Multi-Use Systems
  - IIP Partnership w. Northrup Grumman to improve technical readiness for ACE Mission Integrated Radar Subsystem
    » 2010 IIP & 2013 IIP have identified Ka Band (35 GHz) transmit/receive module performance limitations due to thermal management
  - 2013 IIP w. Harris Corporation identified similar thermal problems for radar technologies in SCLP hardware development
  - QuinStar (SBIR Phase 2) High Power Amplifier w. GaN based chips
- Enabling Technology: Improved transmit/receive module will permit use of synthetic aperture radars

Dr. Racette’s Group will meet with NASA/UTRC/WPI to scope issues
Ultra-high Heat Flux Thermal Management: Cross Agency Requirement

High Heat Flux Electronics Cooling

DISTRIBUTION STATEMENT A: Approved for public release; distribution is unlimited.

Current Thermal Technologies

Current S&T

Spacecraft Technology:

GaN Power Amps
Next Gen Electronics
Next generation CPUs

We’d like to fly these technologies on AF spacecraft
But we can only support this heat flux today

New technologies also offer:

• Ease of integration
• Low cost
• Reduced mass
• Reduced complexity
• Reconfigurability
• Thermal Stability

Courtesy of Andrew Williams, USAF