Advances in Electrically Driven Thermal Management

Jeffrey R. Didion
Senior Thermal Engineer
Manager, Nanotechnology Facility
- 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)
Integrated Radar Subsystem ACE & SCLP

- 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
  » Identified Ka Band (35 GHz) transmit/receive module performance limitations due to thermal management

- Enabling Technology: Improved transmit/receive module will permit use of synthetic aperture radars
High Temperature Heat Acquisition: Reduced Thermal Resistance

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. 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,

**Reduced Mass and Volume of Chip**

**Reduced Thermal Resistance**

**High Temperature Heat Acquisition**
High Temperature Heat Rejection

Higher Heat Rejection Temperature
Lower System Thermal Resistance

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
EHD Conduction Phenomenon

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.
1st Generation EHD Conduction Pump
Manifold 2nd Generation EHD Conduction Pumps

- Ultem Electrode Spacers
- Ultem Pump Housing
- SS EHD Electrodes
- Electrical Pins (Redundant)
- SS Cover Plate
- Inlet/Outlet Manifolds
- Inlet/Outlet Tube (welded - preferred)
STP-H5 EHD Conduction Pump Life Test Loop

5 parallel EHD Pumps operating at 1000 Vdc
- ~ 0.43 g/s HFE 7100
- ~1000 Pa

Instrumentation
- Thermal Mass Flow
- 7 TCs

Status: ON ORBIT
- Delivery: February 2015
- Launch: February 2017
STP-H5 EHD Conduction Pump Life Test Loop

GSFC ISEM Experiment (Thomas Flatley PI)
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.
Electrohydrodynamic (EHD) Phenomenon

Interaction between electric field and flow field

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

- Coulomb Force
- Polarization Forces
EHD Di-electrophoretic Force

\[ F_{DEP} = 2\pi a^3 \varepsilon_1 \left( \frac{\varepsilon_2 - \varepsilon_1}{\varepsilon_2 + 2\varepsilon_1} \right) \nabla |E_e|^2 \]
Dielectrophoretic (DEP) Phase Management & Conduction Pump
Dielectrophoretic (DEP) Phase Management & Conduction Pump

Heat flux was incremented initially by 0.25 W/cm² until 2.50 W/cm² was reached. After this point, it was incremented by 0.50 W/cm² until the critical heat flux was reached. The time between heat flux increments was 300 seconds, which allowed the surface temperature to reach steady state (defined above).

The results of all experiments are shown in Figure 72. Heat flux, $q''$, was plotted against the superheat, $\Delta T = (T_{\text{surface}} - T_{\text{sat}})$.

The low heat flux data for all cases from Figure 72 are shown in Figure 73. The error bars show the measurement uncertainty in $\Delta T$. Since uncertainties in heat flux (which have a maximum of ±3.9%) are too low to be visible as vertical error bars, they are not included. For clarity, uncertainty bars in Figure 73 have been removed.

Figure 72: Experimental data for combined EHD- and DEP-enhanced liquid film flow boiling and pool boiling.

Table XII: Maximum systematic error of various measurement devices and experiment uncertainty for chapter 5

<table>
<thead>
<tr>
<th>Measurement</th>
<th>Maximum uncertainty</th>
</tr>
</thead>
<tbody>
<tr>
<td>Temperature</td>
<td>±0.5°C</td>
</tr>
<tr>
<td>Applied voltage to EHD electrodes</td>
<td>±30 VDC</td>
</tr>
<tr>
<td>Applied voltage to DEP electrodes</td>
<td>±50 VDC</td>
</tr>
<tr>
<td>Current measured through EHD electrodes</td>
<td>±20 µA</td>
</tr>
<tr>
<td>Current measured through DEP electrode</td>
<td>±150 µA</td>
</tr>
<tr>
<td>Applied voltage to heater</td>
<td>±0.06V</td>
</tr>
<tr>
<td>Resistance of heater</td>
<td>±0.05Ω</td>
</tr>
<tr>
<td>Absolute pressure</td>
<td>±350 Pa</td>
</tr>
<tr>
<td>Derived quantity</td>
<td></td>
</tr>
<tr>
<td>Superheat, $\Delta T$ (°C)</td>
<td>±0.71°C</td>
</tr>
<tr>
<td>Heat flux, $q''$ (W/cm²)</td>
<td>±3.9%</td>
</tr>
</tbody>
</table>

2 mm liq. film, 0 kV applied EHD potential, DEP electrode removed, $Psat=80.0$ kPa, $Tsat=21.5$°C
2 mm liq. film, 0 kV applied EHD potential, 2.5 kV applied DEP potential, $Psat=78.2$ kPa, $Tsat=20.9$°C
2 mm liq. film, 1.5 kV applied EHD potential, 2.5 kV applied DEP potential, $Psat=78.5$ kPa, $Tsat=21.0$°C
2 mm liq. film, 2.0 kV applied EHD potential, 2.5 kV applied DEP potential, $Psat=78.8$ kPa, $Tsat=21.1$°C
10 mm liq. pool, 0 kV applied EHD potential, 2.5 kV applied DEP potential, $Psat=78.7$ kPa, $Tsat=21.4$°C
Experiment Breadboard Design
• Investigate the flow distribution control in meso-scale with same and reverse EHD conduction pumping direction

• Experimentally investigate the effect of upstream flow velocity on the formation of heterocharge layer in the vicinity of electrodes
EHD Flow Distribution Control
• Flow redistribution with reverse EHD pumping configuration and comparison with the same EHD pumping configuration

• Flow maldistribution correction with reverse EHD pumping configuration and comparison with the same EHD pumping configuration
Measured flow rates w. initially mal-distributed flow: 1.15 mL/min & 1.75 mL/min
EHD Flow Distribution Control: Two-Phase Flow

Measured flow rates (averaged over 1min): initial two-phase flow distribution @ 0.75 mL/min
The reverse pumping direction configuration was more effective than the same pumping direction configuration:

1. More immediate influence on the flow distribution with lower applied EHD conduction pump voltage.
2. Advanced the flow equalization for the maldistribution correction cases.
3. Greater flow separation between the active and inactive branches.