Enhancement of Pool Boiling Heat Transfer Using Nano-Structured Surfaces on Aluminum, Copper & Silicon

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Army Project: Micro/Nano-Structured Micro-Channel Heat Exchangers for Advanced Cooling

- **Military Need & Problem Statement**
  - Military System Energy Management and Cooling
  - Seek Technologies & Design Techniques to Cool Ultra-High Heat Fluxes & Increase System Energy Efficiencies
  - Future advanced lasers, radars, and power electronics
  - Requirement to Develop Compact, Light-Weight, & Low-Cost Thermal Control & Heat Exchange

- **Project Objective**
  - Demonstrate & Quantify the Thermal Performance Enhancement of Advanced Microchannel Heat Exchangers with Micro- and Nano-Structured Surfaces to Cool Ultra-High Thermal Fluxes
  - Scope
    - *Advanced Thermal Management Using Two-Phase Flow Boiling*
    - *Micro-Technology: Microchannel Heat Exchangers*
    - *Nano-Textured Surfacing to Enhance Flow Boiling in Microchannels*

- **Requirements**
  - Transfer Very High Heat Fluxes (i.e., 200-1000 W/cm²)
  - Across Nearly Isothermal Interface Conditions

- **Potential Applications**
  - *Advanced Lasers & Radars*
  - *High-Performance Computers*
  - *Advanced Military Avionics*
  - *Energy Recovery Systems*
  - *Advanced Power Electronics*
Technical Approach

- Couple Nano-Structured Surface Texturing with Flow Boiling to Enhance Critical Heat Flux Capabilities
- Use Microreactor-Assisted Nanomaterials Deposition
  - Increase Nucleation Site Density on Boiling Surfaces
  - Characterize & Control Pore Sizes to:
    - Increase Nucleation Frequency
    - Create Desired Porous Nano-Structure to Foster / Facilitate Fluid Flow to Nucleation Sites
  - Large Surface-Area-to-Volume Ratios Within Microchannel Structures to Accelerate Heat & Mass Transport
- Develop Texturing Patterns & Shapes That Achieve Improved Microchannel Thermal / Fluid Dynamic Performance
Technical Approach

- Nano-Structures Characterized by:
  - Scanning Electron Microscope
  - Morphology
  - Thickness
  - Energy Dispersive Spectroscopy
- Transmission Electron Microscope
  - Nanostructure by HREM
  - Crystal structure by Electron Diffraction
- Atomic Force Microscopy
  - Morphology
  - Pore Geometries
- Nano-Scale Computational Fluid Dynamics Modeling to Support Nano-Texture Design

FEI Tecnai F-20 Field Emission High Resolution TEM (200kV) at PSU.

FEI Sirion FESEM, 30kV Microscope Equipped With Oxford Inca Energy 250 EDX System at PSU.
## Phase I / II Substrate & Textured Materials Selections

<table>
<thead>
<tr>
<th>Textured Materials</th>
<th>Substrate Material Selections</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Aluminum</td>
</tr>
<tr>
<td>ZnO</td>
<td>Surface Characterizations</td>
</tr>
<tr>
<td></td>
<td>Pore Size &amp; Density</td>
</tr>
<tr>
<td></td>
<td>Contact Angle Data</td>
</tr>
<tr>
<td></td>
<td>Pool Boiling Heat Transfer</td>
</tr>
<tr>
<td>Zeolite</td>
<td>Surface Characterizations</td>
</tr>
</tbody>
</table>

- Phase I Focused on Aluminum Substrates
- Aluminum, Silicon, & Copper in Phase II
Surface Characterizations

- Characterized the Nano-Scale Textured Surfaces According to Key Properties
  - Nucleation Site Density
  - Pore Size Distribution

- Established Key Target Attributes to Measure & Characterize in Each Textured Material Surface:
  - Pore Sizes (Absolute & Size Distribution)
  - Interfacial Adhesion Energy (Contact Angle; $\gamma \cdot (1 + \cos \theta) = \Delta W_{SLV}$)
  - Potential Nucleation Site Density
  - Base Texture Material Thermal Conductivity
  - Material Adhesion (establish a “goodness” test, metric, or criteria)
  - Boiling Heat Flux
Project Accomplishments

- **NiO Nanostructures** on Silicon Substrates
  - NiO Nanostructures at different residence time

- **ZnO Nanostructures** on Aluminum Substrates
Project Accomplishments

- **Nanostructures On Various Substrates**
  - **ZnO Nano-Structures on Aluminum Substrates** (March 2008)
    - 1” X 1” Coupon Size
  - **ZnO Nano-Structures on Copper Substrates** (December 2008)
    - 1-3/16” X 1-3/16” Coupon Size
  - Similar to Nano-Structures to on Al
  - Pool Boiling Tests Performed

- **Contact Angle (i.e., Interfacial Surface Energy) is First Critical Heat Transfer Parameter We Characterize**

Contact angle (54.94°)
Contact Angle Studies – Process Parameter Effects

- ZnO Nanostructures on Al Substrate
- $\theta = 20.3^\circ$
- Can Create Super-Hydrophilic Surfaces with $\theta \sim 0^\circ$
- Bare Aluminum Substrate $\theta=104^\circ$
Surface Structure Relationship to Enhancing Boiling Heat Transfer

- Structures Show Important Critical Characteristics Relevant to Enhancing Heat Transfer
  - Hydrophobic & Hydrophilic Characteristics
  - High Pore Densities for Enhanced Nucleation Sites
  - Porous Structure to Allow Fluid Inflow to Keep Nucleation Sites Active
  - Protrusions Increase Active Boiling Area

\[ q''_h = F(n, \sqrt{f}, D_b^2) \]

\[ D_b \approx \theta \cdot \frac{\sigma}{\sqrt{g \cdot (\rho - \rho_v)}} \]  \hspace{1cm} \text{(Fritz Relationship)}

- \( n \) = nucleation site density
- \( f \) = bubble nucleation frequency
- \( f \) is inversely proportional to pore size
Pool Boiling Test Facility (PBTF)

Oxide on Al, 45° Contact Angle
Hydrophobic Surface
Pool Boiling Heat Flux Data

- Several Surfaces Tested & Characterized
- Balance Between Hydrophobic & Hydrophilic Surfaces is Key
- One Hydrophilic Surface Delayed ONB
- ZnO Nano-textured Surface (on Cu) Showed Lower Superheats at High Heat Fluxes (Magenta Triangles)

- Hydrodynamic Limit for Water (Ideal Case)
  - ~ 125 W/cm²
- Zuber Relationship
- Infinite Plate With No Surface Effects
- Too Optimistic
- Haramura & Katta for Water (More Realistic Model)
  - ~108 W/cm²
- Haramura & Katta
- Accounts for Surface Capillarity
Pool Boiling Heat Flux Data

Boiling Heat Transfer Coefficient Definitely Enhanced By Close to an Order of Magnitude

\[ Q = h A (T_{\text{wall}} - T_{\text{sat}}) \]

- Al - Unique Surface (18)
- Cu - 30 Contact Angle (Fl)
- Al - 20 Contact Angle (Fl)
- Bare Al

Heat Transfer Coefficient, kW/m²K

Heat Flux, kW/m²
CHF Vs Contact Angle

- Heat Transfer Dependent on Surface Contact Angle (i.e., Interfacial Surface Energy & Wettability)
  - Balance Between Bubble Dynamics & Surface Fluid Dynamics
  - Strongly Suggest That Critical Heat Flux Is Controlled by Both Surface Characteristics & Hydrodynamics
  - Optimum @ ~ 20°
Pool Boiling Conclusions

- Optimum Balance Between Hydrophobicity & Hydrophilicity On Nano-Textured Surfaces to Maximize Heat Transfer
  - Boiling Appears More Stable, More Normal Bubble Creation, Higher CHF
  - Smaller Work Required for Bubble Creation ((Pioro, Rohsenow, Doerffer, 2004) as Contact Angle Increases
  - However Contact Angle Too High Compromises Surface Fluid Dynamics
  - Decreased Active Vapor Generation Centers (Wang and Dhir, 1993) as Contact Angle Decreases Too Much
- Nano-Texturing on Al Surfaces Exhibited High Heat Fluxes (82 W/cm²)
- Some Evidence That Hydrophilic (i.e., Low Contact Angle) Surface Delays Onset of Nucleate Boiling
- Nanostructured Surfaces on Cu Showing Lower Superheat at High Heat Fluxes
Project Accomplishments

- Computational Fluid Dynamics Analysis
  - First Known Demonstration of Thermally-Driven Bubble Dynamics Using Shan-Chen L-B Techniques
    - Peng-Robinson Equation of State (Clearly Defined Temperatures & Internal Energies)
  - Computation Performed in Non-Dimensional Parameter Space
  - Idealized, Hydrophobic, Circular Nucleation Site

Simple pool boiling bubble dynamics using L-B

Flow boiling bubble dynamics using L-B
Flow Boiling Results To Date

- Achieved 390 W/cm² off Un-Textured Copper Surfaces to Date
  - Shear-Driven Thin-Film Flows
  - Further Work is Required
- Flow Boiling in Microchannels is Quite Challenging Due to Bubble Interactions with Channels
  - Have Experienced Some Channel Blockage by Bubbles
  - Further Work is Necessary to Understand & Control the Phenomenon
- We Have Developed Some New Ideas / Concepts That are a Subject of Invention Disclosures Right Now

Flow boiling test facility to characterize microchannel flow boiling designs for advanced electronic cooling
We are What We Repeatedly do. Excellence, Then, is not an Act, But a Habit.

Aristotle

Questions & Discussion