Synthesis of CRUD and its Effects on Subcooled Flow Boiling

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CASL Meeting
Massachusetts Institute of Technology
30 April 2015
Objectives and Motivation

- This work investigates the effects of synthetic CRUD on boiling heat transfer properties in pool and subcooled flow boiling:
  - Fabricate representative synthetic CRUD on MIT test heaters
  - Measure effects of synthetic CRUD on boiling heat transfer quantities of interest (htc, bubble parameters, CHF, etc.)
CRUD Morphology

- CRUD with roughly 5μm diameter on a 10μm pitch (synthetic CRUD here is ~0.25μm thick)
## CRUD Morphology

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Reactor CRUD</th>
<th>Synthetic CRUD</th>
</tr>
</thead>
<tbody>
<tr>
<td>Composition</td>
<td>Fe$_3$O$_4$, NiO, NiFe$_2$O$_4$, ZrO$_2$</td>
<td>SiO$_2$</td>
</tr>
<tr>
<td>Thickness</td>
<td>10-100 µm</td>
<td>2-10 µm</td>
</tr>
<tr>
<td>Roughness</td>
<td>$R_a \sim 0.5$-3.0 µm</td>
<td>$R_a \sim 0.7-2$ µm</td>
</tr>
<tr>
<td>Wettability (contact angle)</td>
<td>10-30°</td>
<td>10-15°</td>
</tr>
<tr>
<td>Porosity</td>
<td>40-50%</td>
<td>40-60%</td>
</tr>
<tr>
<td>Pore Size</td>
<td>0.1-1.0 µm</td>
<td>$\sim 0.1$ µm</td>
</tr>
<tr>
<td>Chimney Diameter</td>
<td>2-10 µm</td>
<td>5, 10 µm</td>
</tr>
<tr>
<td>Chimney Pitch</td>
<td>5-20 µm</td>
<td>10, 25, 100 µm</td>
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</table>
Mechanisms of Heat Transfer

vapor escapes

capillary wicking

viscous forces

CRUD
Surface Manufacturing

• Synthetic CRUD was manufactured using the following steps:
  1. Creation of photoresist posts
  2. Layer-by-Layer deposition of nanoparticles
  3. Acetone removal of posts
1. Photolithography

- Posts created using positive photoresist (AZ4620), spin coating, and UV exposure

10μm diameter, 25μm pitch
2. Layer-by-Layer Deposition (LbL)

1) Polycation

2) Water

3) Polyanion

4) Water

- **PAH**\(^+\) (Polycation)

- **SiO\(_2\)**\(^-\) (Polyanion)
3. Acetone Post Removal

- Positive photoresist posts can be dissolved in acetone.
- Samples are sonicated in acetone to remove posts and create chimney features.
Surface Manufacturing
Feature Verification

Dektak Prolifometer
• Thickness, roughness, chimney size and spacing

FIB/SEM
• Thickness, pore size
Particle Analysis

- Synthetic CRUD is composed of SiO$_2$ nanoparticles which create more stable films
  - 10nm particle comparative tests between SiO$_2$ and Fe$_3$O$_4$ will be run to ensure results are representative

<table>
<thead>
<tr>
<th>Properties at 298 K</th>
<th>Fe$_3$O$_4$</th>
<th>SiO$_2$</th>
<th>TiO$_2$</th>
<th>NiO</th>
<th>ZnO</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\rho$ (g/cm$^3$)</td>
<td>5.17</td>
<td>2.20</td>
<td>4.17</td>
<td>5.72</td>
<td>5.60</td>
</tr>
<tr>
<td>$k$ (W/m K)</td>
<td>7.0</td>
<td>1.34</td>
<td>8.4</td>
<td>20.2</td>
<td>29</td>
</tr>
<tr>
<td>$c_p$ (J/g K)</td>
<td>0.62</td>
<td>0.74</td>
<td>0.71</td>
<td>0.53</td>
<td>0.50</td>
</tr>
<tr>
<td>$\alpha$ (k/$\rho c_p$) (m$^2$/s)</td>
<td>$2.18 \times 10^{-6}$</td>
<td>$8.23 \times 10^{-7}$</td>
<td>$2.83 \times 10^{-6}$</td>
<td>$6.66 \times 10^{-6}$</td>
<td>$1.04 \times 10^{-5}$</td>
</tr>
<tr>
<td>Surface E (J/m$^2$)</td>
<td>0.79</td>
<td>~1</td>
<td>1.29</td>
<td>2.4</td>
<td>1.31</td>
</tr>
</tbody>
</table>
Thermal resistance proportional to $L/k$

- SiO$_2$ coatings 2-10 μm have an equivalent thermal resistance to CRUD layers 10-100 μm thick

*Thermal resistance proportional to $L/k$
Initial Results

- \( \text{Fe}_3\text{O}_4 \) and \( \text{SiO}_2 \) behave similarly
- CRUD enhances CHF and HTC roughly 100%

*Apparatus uncertainty \( \sim 1.5\% \)
Test Section

- Quartz test section with large inlet region to fully develop flow
- IR/HSV cameras used to visualize
Deliverables (Test Matrix)

- The following test matrix will be run in a subcooled flow boiling loop to determine the effects of the parameters and test conditions below on boiling quantities of interest:
  - Mass Flux: 150, 250, 500, 750, 1000, 1250 kg/m²s
  - Heat Flux: 100-1600 kW/m²
  - Pressure and Subcooling: 1.05 bar and 5, 10, 15°C

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Advances in Subgrid Models for Subcooled Flow Boiling in Pressurized Water Reactors

Alexandre Guion (Ph.D student), Prof. J. Buongiorno
Massachusetts Institute of Technology, April 2015

Courtesy of Bren Phillips, MIT
RELEVANCE OF 3D LOCAL MODELING SCALE
(DESIGN, SAFETY, COMPETITIVENESS)

Adapted from Gloria Faccanoni LaTeX drawing
NEED FOR RESEARCH ON BOILING

Adapted from Bren Phillips PhD Thesis, MIT

NEED FOR RESEARCH ON BOILING

Kurul and Podowski†: \( q'' = q''_{\text{conv}} + q''_{\text{quench}} + q''_{\text{evap}} \)

NEED FOR RESEARCH ON BOILING

Kurul and Podowski†: \( q'' = q''_{\text{conv}} + q''_{\text{quench}} + q''_{\text{evap}} \)

\[
q''_{\text{evap}} = \frac{\pi}{6} \rho_v h_f D_d N_{\text{sites}} f
\]

1. Fundamentals of boiling

2. Ph.D work and contributions

3. Conclusions
FUNDAMENTALS OF BOILING

†S. Jung, H. Kim, Simultaneous measurements of liquid-vapour phase and temperature distributions on boiling surface with synchronized infrared thermometry and total internal reflection techniques, NURETH-15 Italy, May 12-17, 2013

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S. Jung, H. Kim, Simultaneous measurements of liquid-vapour phase and temperature distributions on boiling surface with synchronized infrared thermometry and total internal reflection techniques, NURETH-15 Italy, May 12-17, 2013
Existence of microlayer

†S. Jung, H. Kim, Simultaneous measurements of liquid-vapour phase and temperature distributions on boiling surface with synchronized infrared thermometry and total internal reflection techniques, NURETH-15 Italy, May 12-17, 2013
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MULTIPLE LENGTH SCALES OF BOILING

Courtesy of Dustin Langewisch, MIT
MULTIPLE TIME SCALES OF BOILING

MULTIPLE TIME SCALES OF BOILING

MULTIPLE TIME SCALES OF BOILING

MULTIPLE TIME SCALES OF BOILING

- bubble growth
- microlayer formation

MULTIPLE TIME SCALES OF BOILNG


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MAIN GAPS IN LITERATURE

- Absence of data and models for microlayer formation
- Limited validation of microlayer evaporation models*†‡
- Absence of quantification of the effect of the flow for both formation and evaporation phases

‡ V. K. Dhir, Simulation of boiling how far we have come!, ECI International Conference on Boiling Heat Transfer, Florianopolis-SC-Brazil, 3-7 May 2009.
1. Fundamentals of boiling

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3. Conclusions
PH.D WORK AND CONTRIBUTIONS

(1) Microlayer Formation

(2) Microlayer Evaporation

(3) Effect of the Flow
(1) SIMULATION OF MICROLAYER FORMATION

METHOD:

\[ Z_{\text{vapor}} \div (u) \, dV = dV_b \, dt \] (1)

END RESULT:

\[ R_b = f \, \beta_{\mu_v, \rho_v} \, \beta_{v, l}, r_{R_b}, Re, Ca, \beta \] (2)

\[ Re = \beta_{l, U_b, R_b, \mu_l, \rho_l}, Ca = \mu_l, U_b \]
(1) SIMULATION OF MICROLAYER FORMATION

METHOD: \[ \int_{\text{vapor}} \text{div}(\mathbf{u}) \, dV = \frac{dV_b}{dt} \] (1)
SIMULATION OF MICROLAYER FORMATION

METHOD: \[ \int_{\text{vapor}} \text{div}(\mathbf{u}) \, dV = \frac{dV_b}{dt} \] (1)

END RESULT: \[ \frac{\delta}{R_b} = f \left( \frac{\mu_v}{\mu_l}, \frac{\rho_v}{\rho_l}, \frac{r}{R_b}, Re, Ca, \theta \right) \] (2)

\[ Re = \frac{\rho_l U_b R_b}{\mu_l}, \quad Ca = \frac{\mu_l U_b}{\sigma} \]

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Advanced Boiling Simulations
(1) SIMULATION OF MICROLAYER FORMATION

With Gerris flow solver (incompressible Navier-Stokes, VOF interface tracking, surface tension, Adaptive Mesh Refinement)

<table>
<thead>
<tr>
<th>Viscosity ratio</th>
<th>Density ratio</th>
<th>Interface Velocity</th>
<th>Reynolds number</th>
<th>Capillary number</th>
<th>Contact Angle</th>
<th>Domain size (r x z)</th>
<th>Mesh size Min-Max</th>
<th>Time simulated</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.0429 (1x) [-]</td>
<td>6.3e-04 [-]</td>
<td>10 [m/s]</td>
<td>342*(1+t) t in us</td>
<td>4.8e-02 [-]</td>
<td>10 [degrees]</td>
<td>384 x 384 [microns]</td>
<td>32/2^2 to 32/2^6 [microns]</td>
<td>0 - 25 [us]</td>
</tr>
</tbody>
</table>

![Graph](image)

- Slope: 10 m/s
SIMULATION OF MICROLAYER FORMATION

![Graph showing microlayer thickness versus radial distance](image)

**Thickness [microns]**

**r, radial distance [microns]**

- **5 us**
- **10 us**

- **t=5us**
- **t=10us**
(2) NEED FOR SUBGRID MODEL

REFERENCE POOL BOILING CASE with TransAT (2-phase, Level-Set, Mass Transfer, Conjugate Heat Transfer)

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Advanced Boiling Simulations
(2) SUBGRID MODEL† IMPLEMENTATION

Evaporation model derived from first principles

Subgrid model implemented in TransAT

\[ \partial_t \delta = - \frac{k_l}{\rho_f h_{fg}} \frac{T_w - T_{sat}}{\delta} \]

† A. Guion, D. Langewisch, J. Buongiorno, Dynamics of the liquid microlayer underneath a vapor bubble growing at a heated wall, Proceedings of the ASME Summer Heat Transfer Conference HT2013 July 14-19, 2013, Minneapolis, MN, USA.

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(2) CONSISTENT GROWTH SCALES
(2) **SUBGRID IMPLEMENTATION VALIDATED**
(2) CONSISTENT SENSITIVITY TO INITIAL SHAPE

[Diagram showing the consistent sensitivity to initial shape with two different initial shapes and a graph showing the equivalent radius over time.]
1. Fundamentals of boiling

2. Ph.D work and contributions

3. Conclusions
CONCLUSIONS

(1) Microlayer Formation

(2) Microlayer Evaporation

(3) Effect of the Flow

Ongoing
Both atmospheric and PWR pressures

Ongoing
Validation against experimental pool boiling benchmark

Future Work