CFD-Based DNB Analysis Methods

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What is challenging about DNB? ... why using CFD

...what comes to mind?

- Violent transition
- Complex physics
- Lack of understanding
- Decades of research
- "Moonshot" (Yadigaroglu, 2014)

...what is the opportunity?

- New generation of experiments
- Mature computational “framework” for CFD
## What is challenging about DNB? … why using CFD

<table>
<thead>
<tr>
<th>Numerical Correlations</th>
<th>Mechanistic Models</th>
<th>Look-Up Tables</th>
</tr>
</thead>
<tbody>
<tr>
<td>Simply correlate data to a mathematical formula</td>
<td>Attempts to model the physics of the phenomena</td>
<td>Tabulate results for all the operating conditions</td>
</tr>
</tbody>
</table>

- **Westinghouse W-3 Correlation**
- **Biasi Correlation**
- **Bowring Correlation**

- **Vapor Column**
  - Zuber 1959
- **Near Wall Bubble Crowding**
  - Weisman & Pei 1983
- **Liquid Sublayer Dryout**
  - Katto 1994

- **Groeneveld CHF Look-Up Table**
- **Kirillov CHF Look-Up Table**
  - 1991

- **Subchannel codes**
  - FLICA4, THINC, COBRA-TF
- **Subchannel codes**
  - COBRA-IIIC, COBRA-IV-I, MATRA
- **System Codes**
  - RELAP5, TRACE, CATHARE

**Existing models**
- Developed a posteriori from experiments
- Some models do not try to model the physics at all
- Use of simple geometries (tubes, channels, annulus…)
- Lack predictive power outside validated range
- No local surface effect (macro hydrodynamics)

**Need for CFD approaches:**
- Capture 3D effects (complex geometries)
- Incorporate first principle mechanisms for real predictions

Proof-of-Concept of DeCART/STAR-CCM+/MAMBA Coupled Simulation (...). CASL report, 2012
Status of DNB Capabilities in CFD – FY16
## FY16 Completed Milestones (DNB)

<table>
<thead>
<tr>
<th>Milestone #</th>
<th>Task Code</th>
<th>Responsible</th>
<th>Description</th>
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<tr>
<td>#1483</td>
<td>L2:THM.P13.02</td>
<td>Baglietto</td>
<td>Demonstrate DNB analysis methods using CFD (FY16.CASL.009)</td>
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<tr>
<td>#1489</td>
<td>L3:THM.CFD.P13.04</td>
<td>Seung Jun Kim</td>
<td>LANL - DNB Assessment</td>
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<tr>
<td>#1498</td>
<td>L3:THM.CLS.P13.09</td>
<td>Buongiorno</td>
<td>Experimental study of subcooled flow boiling heat transfer up to the DNB limit for both uncoated and synthetically CRUD-ed surfaces</td>
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<tr>
<td>#1503</td>
<td>L3:THM.CLS.P13.01</td>
<td>Balu Nadiga</td>
<td>Hydrodynamic closure evaluation in multiphase flow using STAR-CCM+ and NEPTUNE</td>
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<tr>
<td>#1493</td>
<td>L3:THM.CLS.P13.03</td>
<td>Junsoo Yoo</td>
<td>Boiling Validation against TAMU Data</td>
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<tr>
<td>#1492</td>
<td>L3:THM.CLS.P13.05</td>
<td>Baglietto</td>
<td>Robust hydrodynamic closures advancements for PWR application.</td>
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<td>#1497</td>
<td>L3:THM.CLS.P13.08</td>
<td>Hassan</td>
<td>Device-Scale Multiphase Flow Experiments and Data Analysis</td>
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<td>#1500</td>
<td>L3:THM.CFD.P13.01</td>
<td>Podowski</td>
<td>Analyze Mechanistic Models of Subcooled Boiling and CHF in LWR Fuel Assemblies with Spacers</td>
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<tr>
<td>#1495</td>
<td>L3:THM.CLS.P13.02</td>
<td>Luo</td>
<td>Advanced Boiling Algorithms [Test bed openFOAM]</td>
</tr>
</tbody>
</table>
GEN-I and GEN-II DNB methods in CFD

multi-step and multi-approach

- Based on validated GEN-I Hydrodynamic closures
- Macrolayer DNB Method implemented in STAR-CCM+ (a la Weismann-Pei)
- Single Pipe flow DNB test performed at LANL confirm feasibility of the approach
- Currently working on 5x5 performance evaluation

- GEN-II Partitioning Completion
  - Extensive completion / validation activities
- GEN-II Hydrodynamic Closure
  - Lift for higher void fraction / robustness
  - Turbulence and wall treatment for improved predictions
- Novel DNB resolution approach
  - Key to generality
  - Includes surface effects
  - Tight schedule for assessment

Jun Kim – LANL
Etienne Demarly - MIT

GEN-I Many variants but one approach...

- **DNB Forcing Function**

\[ \Phi''_{\text{wall}} = (1 - f) \times (\Phi''_{fc} + \Phi''_q + \Phi''_{ev}) + f \times \Phi''_{gas} \]

- A priori Heat Transfer mode transition
- Bubbly layer theory. Critical near-wall void fraction
- \( \alpha_c = 0.82 \) (Weisman & Pei 1983)
- \( f \) = smooth blending function between 0 and 1

\[ \overline{\alpha_c} : \text{average void fraction in the near wall cell} \]
Low errors in optimized cases
High errors non standard cases
High sensitivity on:
  - Mesh
  - Physics models
Could be partly related to limitations of the Hydrodynamic closures

1. Implementation of “Gen I” DNB Model

LANL in charge of assessment will present current status

Currently working on 5x5 application

- Single tube (8mm)
- Pressure: 100 bar
- Inlet quality: -0.24
- Inlet mass flux: 3000 kg/m²s
- Constant heat flux
- Reference CHF: Groeneveld 2006
- Constant lift

\[ Q_{CDF} = 5.04 \text{MW} \]
\[ Q_{LUT} = 4.666 \text{MW} \]
\[ \varepsilon = 8\% \]

\[ Q_{CDF} = 5.0 \text{MW (no DNB)} \]
\[ Q_{LUT} = \emptyset \]
\[ \varepsilon > 30\% \]

\[ Q_{CDF} = 4.35 \text{MW} \]
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\[ \varepsilon = -16.2\% \]

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CFD methodology for DNB model and boiling curve generation

**CFD methodology for DNB model**
- Define the DNB test condition (P, G, T_{sat})
- Set up the boiling closure and the DNB trigger criterion
- Run with zero heat flux for the initial condition
- Increase the applied heat flux (q') by 0.05 M/m²
- Check the thermal equilibrium parameters (i.e. saturation of wall and outlet temperature)
  - If the thermal equilibrium parameters is converged: yes
  - No, temperature excursion observed
- Determine the CHF value for the test condition
  - Generate the boiling curve

**Wall temperature monitoring**

**Boiling curve with DNB point**

- Boiling curve + DNB point generated by CFD: water boiling at 138 bar (P), 940 kg/m²s (G), 40°C subcooled (T_{sat})

**Jun Kim – LANL, Etienne Demarly - MIT**
Preliminary result for DNB validation in M-CFD

- Show reasonable agreement between Exp. and CFD
- Best prediction with current boiling model at high mass flux & low subcooled flow

Jun Kim – LANL
Etienne Demarly - MIT
PWR Fuel Geometries

- Currently starting evaluating model applicability and BPG for 5x5 assembly
Challenges of “industrial” application
Challenges of “industrial” application
DNB Experimental Observation

**Micro/nano surface CHF enhancements**

**Macro vs Micro thermal hydraulic origin of DNB**

**Dry Area Fraction**


_B. Kim, H. Lee. Interfacial wicking dynamics (…)) 2014_

_J. Jung, S. J. Kim. Observations of the CHF process(…) 2014_
2. Develop a consistent new DNB representation in CFD based

\[ \Phi_{wall}^{''} = (1 - f) \times \Phi_{NB}^{''} + f \times \Phi_{gas}^{''} \]

\[ f = \frac{A_{Dry}}{A_{Dry} + A_{Wet}} \]

Parameters of importance for \( f \):

\[ A_{Dry} \left( N^{''}, t_w, t_g, D_d, \ldots \right) \]
+ Surface properties (surface tension, cavities, \( C_p \))
+ Dry Spot clustering dynamics
2. Develop a consistent new DNB representation in CFD

Single-phase (liquid) forced convection

\[ \Phi_{fc} = \frac{\rho_l c_p l u_T}{t^+} (\Delta T_{sup} + \Delta T_{sub}) \]

Evaporation via bubble generation

\[ \Phi_{ev} = \frac{4}{3} \pi \left( \frac{D_d}{2} \right)^3 \rho g h_f g f N'' \]

Quenching

\[ \Phi_q = \rho_h c_{ph} \Delta T_h v_q f N'' \]

Sliding conduction (sliding bubbles)

\[ \Phi_{sc} = \frac{2k_l (T_w + T_l)}{\sqrt{\pi \eta_l t^*}} \alpha_{sl} t^* f N'' \]

Depiction of the heat flux partitioning for subcooled flow boiling.
Drive development with measurements
High-speed IR phase detection and high-speed video

- Average temperature and heat flux
- Nucleation site density
- Bubble departure frequency
- Bubble departure and lift-off diameter
- Sliding distance

Partitioned heat-fluxes
- $q''_e$
- $q''_{sc}$
- $q''_q$
- $q''_{fc}$

Fundamental quantities
- $N_d$
- $t_w$
- $t_g$
- $f$
- $D_d$
- $D_l$
- $h_{fc}$
- $d_{sl}$
- $A_{wet}$
- $l_{cl}$...
Examples of IR phase detection capabilities

zoom on a nucleation site
3. GEN-II Experiment for High Heat Flux

- Up to 10 bars
- Ambient temperature to saturation
- 400 to 1250 kg/m²/s
- Up to CHF
- Synchronized IR and HSV
- Advanced post-processing algorithms

ENABLE DIRECT MEASUREMENT OF HEAT FLUX PARTITIONING
Driven by *new data analysis techniques*

**Nucleation Sites interaction**

The current best practice for NSD modeling is the Hibiki-Ishii correlation (2003).
- Semi-empirical modeling of cavity activations on the heater
- Correlation behavior is exponential by nature and **unbounded**.
- Impossible to use as-is in a numerical simulation
- In reality, there are only so many bubbles a surface can sustain.

$$N''_{HI}(\Delta T) \propto e^{k\Delta T}$$

Number of activated cavities ≠ Number of active bubble generating sites.

**Complete Spatial Randomness:**

$$P = 1 - e^{(-\pi D d^2 N'')}$$

Proposed modification to Hibiki-Ishii correlation:

$$N''_{mod}(\Delta T) = N''_{HI}(\Delta T)e^{-\pi D d^2 N''_{mod}(\Delta T)}$$

**Automatic data post-processing framework**

**Nucleation site Detection via IR post-processing**

1. Creation of a metric:

$$F(x, y) = \frac{\sum_{k=0}^{N_{max}} T(x, y, k + 1) - T(x, y, t)}{\Delta t}$$

2. Gaussian smoothing (optional)
3. Detection of local maxima
4. Binary masking
5. Individual site frequency analysis
6. Spectral analysis of the departure frequency for each case
MIT Flow Boiling experiment (2013)

- High speed IR camera acquisition
- Post-processing of $T$ and $\phi$
  - Nucleation site detection
  - Frequency analysis

Time integral of the Temperature/Heat Flux derivative (rate of change) + pre/post processing

- Test 293: $P=1.5b$, $G=1500kg/m^2s$, $T_{sub}=10C$, $\phi=600kW/m^2$
- Test 303: $P=1.5b$, $G=2500kg/m^2s$, $T_{sub}=10C$, $\phi=600kW/m^2$
- Test 314: $P=1.5b$, $G=5000kg/m^2s$, $T_{sub}=10C$, $\phi=600kW/m^2$
Frequency Analysis

- From a nucleation site location:
  - Signal extraction
  - Detection of nucleation events
  - Statistical analysis (mean, std)
  - Dependency to TH conditions for the same site
  - Statistical distribution for each case
## FY17 Milestones

<table>
<thead>
<tr>
<th>Milestone</th>
<th>Project</th>
<th>Type</th>
<th>Responsible</th>
<th>Status</th>
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<tbody>
<tr>
<td>#1948</td>
<td>L1:CASL.P15.01</td>
<td>new</td>
<td>Baglietto</td>
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<td>#1660</td>
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<td>new</td>
<td>Baglietto</td>
<td>PoR-15</td>
</tr>
</tbody>
</table>

- **Develop, Demonstrate and Assess Advanced CFD-based Capability for Prediction of DNB**
- 1-Industrial DNB Method Assessment
- **GEN-II DNB Method Completion and Assessment**
- Full Scope DNB Tests with dedicated post processing
- STAR-CCM+ V&V Assessment Report for DNB
- GEN-II DNB Testing and Validation
- Data Driven DNB advancements
- Hydrodynamic Closures for DNB
CHF flow boiling experiments at MIT

IR space resolution 100 um
IR time resolution 0.4 ms
Growth of the dry spot at 2.45 MW/m$^2$/K
10 K subcooling, 500 kg/m$^2$/s, 1 atm

+0 ms  +240 ms  +480 ms  +720 ms  +960 ms

TEMPERATURE [°C]