CASL Industry Council Meeting
April 4-5, 2017 - Charleston, South Carolina

CASL CFD-Based DNB Analysis Methods

Emilio Baglietto, MIT
Dave Pointer, ORNL
Objectives and motivation
... aka why using CFD?

- Flow and temperature distributions (and DNB) have strong 3-dimensional effects
- Subchannel approach does include 3D effects (unless mapped from CFD)
- DNB is a strongly local phenomenon
- Subchannel Approach does not have “local information”
- CFD allows predictive design (extremely wide applicability range)
- CFD naturally supports local surface effects treatment for full predictive capability
- Predictive sensitivity to local surface characteristics is referred to here as GEN-II.

Divide and Conquer
*a great challenge requires a great team*

1. Surface Boiling Representation
2. Hydrodynamic Closures
   2b. DNS and Experiments for Closures
3. DNB modeling in CFD
4. Fundamental Validation
5. DNB Testing

- A. Manera, V. Petrov [U-Michigan]
- N.T. Dinh, Igor Bolotnov, H. Luo [NCSU]
- M. Podowski [RPI]
- Y. Hassan, C. E. Estrada-Pérez [TAMU]
- G. Tryggvason, J. Lu [Notre Dame]
- M. Bucci, J. Buongiorno [MIT]
- S. J. Kim, B. Nadiga [LANL]
- JS. Yoo, S.J Yoon [INL]
# FY17 Milestones *(a subset)*

<table>
<thead>
<tr>
<th>#</th>
<th>Level</th>
<th>Code</th>
<th>New</th>
<th>Responsible</th>
<th>PoR</th>
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- **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&amp;V Assessment Report for DNB**
- **GEN-II DNB Testing and Validation**
- **Data Driven DNB advancements**
- **Hydrodynamic Closures for DNB**
Balancing innovation and delivery

*agile approach for multi-step delivery*

**Physical Representation**

1. Baseline lumped closures + Macrolayer DNB - **GEN – IA**

2. CASL advanced hydrodynamic closures + Macrolayer DNB - **GEN – IB**

3. Complete GEN-II boiling plus + Microlayer - **GEN – II**

**Details**

- Kurul-Podowski Boiling
- Simplified RPI Hydrodynamic Closures
- Macrolayer DNB model assessed on single tube tests *[no calibration]*
- Currently Performing NMV and MV tests
- Demonstrates Potential of the approach, and identifies focus for calibration
Balancing innovation and delivery

**agile approach for multi-step delivery**

**Physical Representation**

1. Baseline lumped closures + Macrolayer DNB - **GEN – IA**
2. CASL advanced hydrodynamic closures + Macrolayer DNB - **GEN – IB**
3. Complete GEN-II boiling plus + Microlayer - **GEN – II**

**Details**

- Kurul-Podowski Boiling
- Advanced Hydrodynamic Closures for improved generality
- *Improved description of near wall void distribution*
- Collaboration with CEA/EDF on closure assessment
- Candidate #2 for 2017 DNB milestone
Balancing innovation and delivery

*agile approach for multi-step delivery*

Physical Representation

1. Baseline lumped closures + Macrolayer DNB - GEN – IA

2. CASL advanced hydrodynamic closures + Macrolayer DNB - GEN – IB

3. Complete GEN-II boiling plus + Microlayer - GEN – II

Details

- Novel Physics Based Wall Boiling Description
- Complete Hydrodynamic Closures Including bubble migration at higher void fraction
- Novel Microlayer DNB capturing, based on heat balance on surface
- Currently Performing assessment of Hydrodynamic Closures
- Currently Demonstrating new DNB capturing approach
Status of GEN-IA DNB Assessment
GEN-I Macrolayer DNB description
leveraging extensive application history

- **DNB Forcing Function**

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

- 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

\[ \Phi_{wall} = (1 - f) \times (\Phi_{fc} + \Phi_{q} + \Phi_{ev}) + f \times \Phi_{gas} \]

\( \Phi_{wall}^{''} \): average void fraction in the near wall cell
CFD Implementation of GEN-I DNB Model

Macrolayer model is based on local void fraction and therefore requires calibration

- 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

\[ Q_{CFD} = 5.04 \text{MW} \]
\[ Q_{LUT} = 4.666 \text{MW} \]
\[ \epsilon = 8\% \]

\[ Q_{CFD} = 4.35 \text{MW} \]
\[ Q_{LUT} = 5.189 \text{MW} \]
\[ \epsilon = -16.2\% \]

\[ Q_{CFD} = 5.0 \text{MW (no DNB)} \]
\[ Q_{LUT} = \emptyset \]
\[ \epsilon > 30\% \]
CFD methodology for DNB model and boiling curve generation

CFD methodology for DNB model

- Define the DNB test condition (P,G,T<sub>i</sub>)
- 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 W/m²
- Check the thermal equilibrium parameters (i.e. saturation of wall and outlet temperature)
  - If the thermal equilibrium parameters is converged
    - Yes
      - Determine the CHF value for the test condition
      - Generate the boiling curve
  - No, temperature excursion observed

Wall temperature monitoring

Boiling curve with DNB point

Jun Kim – LANL, Etienne Demarly - MIT
GEN-IA DNB validation for Single Tube

The effect of Inlet Subcooling on DNB value shown in both EXP (Weatherhead, 1963) and CFD (LANL, 2016)

- 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
5x5 DNB validation for NMV Spacer

**Geometrical representations of rods and spacer in the model**

Full geometry 5x5 DNB modeling domain
Height: 3m (five spans included)
Mixed heat flux (6 hot rods + 19 cold rods)
DNB data available from WEC report

**Goal: 5x5 DNB validation**
Baseline DNB validation test case
5x5 fuel bundle with NMV spacer

- **DNB model is first demonstrated on test case (run#27)**
  - Inlet temp. = 330°C
  - Inlet velocity = 5.3 m/s
  - System pressure = 165 bar
  - Five spacers with 25 rods
  - 6 hot rods, 19 cold rods
  - No contact between Rods and Spacer
  - Incremental heat flux of 0.1MW/m²

- The maximum rod wall temperature is monitored as the heat flux gradually increases.
First DNB simulation result for full span

- First DNB validation test for full span WEC test
- Lessons learned from previous DNB tests are applied here
- ~11% deviation between CFD prediction and Exp. Measurement of run#27

Experimental DNB measurement (xxxMW/m2)
WEC DNB report Run-27#
~11% deviation between CFD prediction and Exp. Measurement.

Note, the deviation of DNB prediction in pipe flow DNB test was ~15%
(see FY16 L2,L3 DNB validation milestone report)
DNB validation campaign \textit{[Broad scope]} 
P=165 bar tests, 13 test cases

<table>
<thead>
<tr>
<th>Run (Ø)</th>
<th>Pressure (bar)</th>
<th>Inlet temp. (K)</th>
<th>Mass flux (G) (\rightarrow) Velocity (m/s)</th>
<th>Exp.-DNB (MW/m²)</th>
<th>CFD-DNB (MW/m²)</th>
<th>Deviation (%)</th>
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<td>#27</td>
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<td>330.604C (\rightarrow) 603.7K</td>
<td>3050.844G (\rightarrow) 5.3 m/s</td>
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<td>16.9%</td>
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<td>330.082C (\rightarrow) 603.2K</td>
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<td>52.0%</td>
<td>20.0%</td>
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\textit{Subcooled level less than 70K cases show reasonable DNB prediction capability (<20%)}

Mass flux does not affect the DNB prediction
### DNB validation campaign 2
Relatively low subcooled ($\Delta T_{\text{sub}} < 50K$) group

<table>
<thead>
<tr>
<th>Run #</th>
<th>Pressure(bar)</th>
<th>Inlet temp.(K)</th>
<th>Mass flux → Velocity (m/s)</th>
<th>DNB (MW/m²)</th>
<th>CFD-DNB</th>
<th>Deviation</th>
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<tbody>
<tr>
<td>#27</td>
<td>160~165</td>
<td>330.6°C → 603.7K</td>
<td>3050.8G → 5.3 m/s</td>
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<td>-11.5%</td>
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<td>#28</td>
<td>160~165</td>
<td>330.6 → 603.7 K</td>
<td>3046.5 → 5.3 m/s</td>
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<td>-9.1%</td>
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<td>312.7 → 585.9 K</td>
<td>3021.8 → 5.3 m/s</td>
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<td>0.8%</td>
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<td>#34</td>
<td>160~165</td>
<td>330.1 → 603.3 K</td>
<td>3668.1 → 6.4m/s</td>
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<td>-15.4%</td>
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<td>#35</td>
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<td>329.6 → 602.8 K</td>
<td>3668.1 → 6.4m/s</td>
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<td>-12.7%</td>
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<td>3623.6 → 6.3m/s</td>
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<td>310.9 → 584.1 K</td>
<td>2262.6 → 3.9m/s</td>
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<td>1245.7 → 2.2 m/s</td>
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<td>1202.3 → 2.1 m/s</td>
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<td>5.3%</td>
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</table>

Mass flux/density = velocity  
$T_{\text{sat}} = 623K$, Density = 575kg/m³ @ p=160-165 bar
DNB validation shows good prediction capability

test group (11 cases: 160+bar, 1200~3600G, <50K subcooled)

- For Low subcooling cases the GEN-IA boiling model predicts the Departure of Nucleate Boiling (DNB) points within 15% deviation from measurements in the PWR operating condition
- For High subcooling errors as large as 50% are observed [Pre-calibration]
GEN-IB Closures Assessment
Robustness and portability of models
demonstrated robust applicability to bubbly flow

- Liu and Bankoff databases selected (in collaboration with CEA/EDF)
- Upward bubbly flow, 42 test conditions, $Re \sim 50,000$
- **OBJECTIVE:** demonstrate a minimal set of closures with robust applicability to bubbly flow

All 42 cases used for full assessment, representative subset shown here

Robustness and portability of models
demonstrated robust applicability to bubbly flow

- Liu and Bankoff databases selected (in collaboration with CEA/EDF)
- Upward bubbly flow, 42 test conditions, $Re \sim 50,000$
- OBJECTIVE: demonstrate a minimal set of closures with robust applicability to bubbly flow

D = 38 mm

All 42 cases used for full assessment, representative subset shown here

Near wall description accuracy
extend generality of DNB predictions

- M-CFD does not resolve the near wall region
- Accumulation of vapor in the near wall cells is used to capture DNB in GEN-I models
- Existing treatment of near wall adopt artificial wall lubrication force
- CASL has developed a more consistent Regularization of turbulent dispersion near wall

Assumption
Spherical bubbles are attached to the wall OR are large enough compared to the gap between bubbles and the wall

![Diagram showing gas volume fraction profiles for selected cases from Liu and Bankoff experimental database.](image-url)
Status of GEN-II DNB Completion
GEN-II Heat Partitioning in STAR-CCM+

- GEN-II boiling being currently being tested in STAR-CCM+ v.11.06 (collaboration with SIEMENS-PLM)
- Modern software practices, to guarantee quality and delivery to CASL partners
- Key component for GEN-II DNB
- Experimental work is providing separate assessment of all model terms

- Dedicated DNB test delivered for GEN-II assessment
- Up to 10 bars
- Ambient temperature to saturation
- 400 to 1250 kg/m²/s
- Focus on model components and heat partitioning measurements

From M. Bucci (mbucci@mit.edu)
GEN-II Heat Partitioning + DNB

Dedicated data analysis framework

Nucleation site Detection via IR post-processing

1. Creation of a metric:
   \[ F(x, y) = \sum_{k=0}^{N_{max}} | T(x, y, k + 1) - T(x, y, t) | \]

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

\[ \Phi''_{wall} = (1 - K_{dry}) \times (\Phi''_{fc} + \Phi''_{q} + \Phi''_{ev} + \Phi''_{sc}) + K_{Dry} \times \Phi''_{gas} \]

\[ \Phi''_{fc} = \frac{\rho_l c_{pl} u\tau}{t^+} (\Delta T_{sup} + \Delta T_{sub}) \]

\[ \Phi''_{q} = \rho_h c_{ph} \Delta T_h V_q fN'' \]

\[ \Phi''_{ev} = \frac{4}{3} \pi \left( \frac{D_d}{2} \right)^3 \rho_g h_{fg} fN'' \]

\[ \Phi''_{sc} = \frac{2k_l (T_W + T_l)}{\sqrt{\pi \eta_l t^*}} a_{sl} t^* fN'' \]

\[ K_{Dry} = f t_g N'' \pi \left( \frac{D_{Dry}}{2} \right)^2 \]
GEN-II DNB Model Demonstration

- DNB is predicted obtained as limiting condition for the heat flux on a boiling surface, without any ad-hoc mechanism
- Preliminary testing confirms ability to resolve the boiling curve behavior
- POR-14 experimental measurements currently being used to quantitatively assess the model

GEN-II model aims at statistically reproducing the local surface conditions. [wait for the end of the movie, hot dryspot formation DNB].

Growth of the dry spot at 2.45 MW/m²/K

10 K subcooling, 500 kg/m²/s, 1 atm