Better Reactors Grow from Better Simulations

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Contents

- CFD in the Nuclear Industry
  - Why and where
  - The Consortium for Advanced Simulation of Light Water Reactors (CASL)
- Single phase applications and turbulence
  - Applications and challenges
  - The next step → robust turbulence modeling for unsteady phenomena (GTRF, fatigue, thermal mixing, streaming …)
- Multiphase Computational Fluid Dynamics
  - New physical understanding
  - Advanced closures for M-CFD
Why and where CFD?

1. Core and core components
2. Upper Internals
3. Steam Generator Internals
4. Steam Lines
5. PRZ components
6. Pumps and seals
7. Flow mixing, fatigue, shedding
8. Stratification, hydrogen accumulation

www.mnes-us.com
And what about advanced concepts?
CASL: The Consortium for Advanced Simulation of Light Water Reactors
A DOE Energy Innovation Hub for Modeling & Simulation of Nuclear Reactors

**Task 1:** Develop computer models that simulate nuclear power plant operations, forming a “virtual reactor” for the predictive simulation of light water reactors.

**Task 2:** Use computer models to reduce capital and operating costs per unit of energy, …..
Virtual Environment for Reactor Applications

Baseline
- VABOC
- BOA
- ANC9
- VIPRE-W

Thermo-Mechanics
- MAMBA
- PEREGRINE

Geometry / Mesh / DataTransferKit (DTK)
- LIME
- Trilinos
- DAKOTA
- MOOSE

Thermal-Hydraulics
- COBRA-TF
- Hydra-TH
- Drekar
- STAR-CCM+

Neutronics
- XSPProc
- Denovo
- MPACT
- DeCART

Relaps system

Common Input front-end
4-Loop Westinghouse PWR Multi-Physics Model Development

- RPV ID 173”, 193/4 Fuel Assemblies, 13,944 fuel rods (fuel pellets, helium gap), 434 spacers, 148,224 mixing vanes; 1.2 billion cells
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Evaluating PWR Performance and Reliability with Virtual Simulators

Fuel Related Applications

Mature Applications

- **Fuel**
  - ✔ Pressure Drops
  - ✔ Crud (CIPS/CILC)
  - ✔ Vibrations (GTRF)

- **System and BOP**
  - ✔ Transient Mixing
  - ✔ Hot Leg Streaming
  - ✔ Thermal Striping
  - ✔ SG performance
  - ✔ Cooling Towers Interference

- **Fuel Cycle and Beyond Design**
  - ✔ Spent fuel transportation and Storage
Fuel Simulation – Press. Drops

- **Strong Influence of Anisotropic Turbulence**
- **Necessary to Adopt an Accurate Anisotropic Turbulence Model** – current optimal solution is NLEVM

QKE = Quadratic k-e
Baglietto and Ninokata

SST = Menter Shear Stress Transport mode

**Press. Drop**

**Reynolds Number**

- DP6 (psi)
- CFD QKE
- CFD Ke
- CFD SST
3-D Distributions for Crud Risk Evaluation

J. Yan, B. Kochunas, M. Hursin, T. Downar, A. Godfrey, Z. Karoutas E. Baglietto – NURETH 14

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Better Reactors Grow from Better Simulations
Fluid Structure Interactions Design

CFD Forcing / VITRAN Validation

Towards Self-adaptive Turbulence

- Based on Baglietto 2006 Anisotropic Closure
- Extend to robust PANS formulation
- Self adapt resolution to flow requirements

Currently validating a fundamentally new self-adaptive local evaluation of $R_\Delta$

\[ \mu_t = R_\Delta f_\mu \frac{C_\mu \rho k^2}{\varepsilon} \]

$R_\Delta = 1$ URANS
$R_\Delta = 0.4$ LES
$R_\Delta = 0$ DNS
Better Reactors Grow from Better Simulations

- LES
- PANS
- URANS

Continuous resolution
Challenges

- 2mm grid
- 4mm grid
- Consistency
- Grid convergence
Multiphase CFD

... new physical understanding
MIT Team

Advanced M-CFD

Boiling Model Development

THM.CLS.P7.09 - 8/30/2013
Development of hardened CMFD boiling model. Release and testing of new approach aiming at robust sensitivity to surface and flow parameters, with built-in extension to DNB.

Prof. Emilio Baglietto
Lindsey Gilman (PhD student)

Rosie Sugrue (graduate student)

Momentum Closures

THM.CLS.P7.10 - 8/30/2013
Advanced M-CLs based on ITM/DNS and experiments

Dedicated Experimental Database

THM.CLS.P7.01 - 6/28/2013
Experimental database for subcooled flow boiling

Prof. Jacopo Buongiorno
Dr. Thomas McKrell (research scientist)
Bren Phillips (PhD student)

DNS/ITM Database

THM.CLS.P6.01 - 3/29/2013
Dedicated model for microlayer heat transfer

THM.CLS.P7.03 - 9/30/2013
Challenge Simulations of Boiling Phenomena. Nucleation, growth and bubble departure.

Dr. Gustavo Rabello (post-doc)
Alexandre Guion (graduate student)
EMP improvement with MIT flow boiling experiments

- Microscale experiments for model formulation
- DNS + Experiments
Advanced Wall Boiling Closures
Leveraging new physical Understanding

- The approach:
  - Adopt the idea of “heat partitioning” approach
  - Newly Formulated Flow Boiling Partitioning
  - Specific design for DNB limit capturing

High-speed video from above the boiling surface - IR thermography from below the boiling surface

Post processing gives nucleation site density, bubble departure frequency, local heat transfer coefficient (J. Buongiorno, MIT)

Significant bubble coalescence near the heated wall of an annular flow channel as indicated by the increasing bubble mushroom region (Tu et al., 2005).
Mechanistic approach

- Flexible model
- Proven application record

So why a new model? (hopefully start addressing the fundamental question)

- There are too many components but listing some fundamental ones:
  - Increased synergy with experimental “micro” measurements
  - Extended applicability (lower/higher vapor generation)
  - Include modeling toward limiting behavior (CHF)
Novel Mechanistic Flow Boiling Model (2)

Effects of bubble crowding

- Current models are strongly sensitive to active nucleation site density (require the use of experienced based limiters)
- Built in crowding effect eliminates need for limiters
- Prediction of dry surface can be directly verified against experimental measurements
- DNB can be expressed as the limit of this behavior
- Potentially local/scalable model for DNB

Allows tracking physical limits
Novel Mechanistic Flow Boiling Model (3)

Evaporative Heat Transfer $q''_e$

- Kurul-Podowski is “a posteriori” concept
- $D_d^3$ behavior
- e.g. $q''_e = 0$ until OSV
- New model targets capturing the real evaporative $q''_e$
- Builds in tracking of physical limits
- Naturally extends to limit behavior without need for new empirical model

$$q''_e = \rho_v h_{fg} \frac{\pi}{6} D_d^3 N'' f \propto S_{microlayer}$$

Need to model the microlayer evaporation – leverage CASL ITM-DNS
Novel Mechanistic Flow Boiling Model (4)

Bubble departure and sliding

- Leverage *improved mechanistic force balance model à la Klausner*:
  - Sugrue, Buongiorno 2013
- Optimal estimation of departure diameter ($D_d$)
- Allows quantifying lift off diameter ($D_l$)
- Accounts for augmented heat transfer
- Accounts for deactivation of nucleation sites …
Novel Mechanistic Flow Boiling Model (5)

Quenching of “walls”
- Currently related to fluid properties (can be combined into evaporative)

Influence of heater material
- Semi-analytical representation of the influence area of the bubble on the heater back to the wall superheat and temperature distribution prior to bubble departure
- Unclear relevance, but minor implementation cost

\[ q''_q = \rho_h c_{p,h}(T_a - T_w)\delta_h \]
Law of the “boiling” wall

- Forced convection should be modified to account for presence of bubble (growing, sliding, departing)
- This is done by introducing an equivalent sand roughness to represent the presence of the bubbles
- Validated vs. representative CASL DNS tests

Generalized correction

- Start from DNS results from ITM-1
- Final corrections will adopt:
  ✓ MIT and TAMU experiments
  ✓ ND and NCSU ITM/DNS

Demonstration of Wall Function correction DNS/LES data for hemispherical obstacles (ITM-1 results)

\[
\frac{y^+}{u^+} = 400 \quad \text{smooth}
\]

\[
R_e = 400, \quad R_a = 0.00327 \, \text{m}
\]
Targeting generality
(simplified version... more to come)

- **Microlayer Evaporation** → **DNS Simulations**
- **Active Nucleation Site Density** → **Experimental Meas.**
- **Departure diameter ($D_d$)** → **Sugrue et al.**
- **Departure frequency** → **Consistent with Sugrue et al.**
- **Sliding (and coalesc.) Bubbles** → **Dedicated measurements**
- **Quenching** → **... working on it**

**Robust Boiling Model**
Quickly … on momentum closure

- We need a robust closure formulation for extended application
- *Robust* requires realistic physics, don’t always blame the code
- The general approach requires a physical under-relaxation (which is simply physics) a homework example:

Each region adopts specific Lift and Drag Formulations (continuous)

Local Topology Recognition

- Z=1.5m
- Flow regime observation station

Kwon-Chiang Integral Interaction Length
Why physics based ??

Flow regime observation station:
- $Z=2\text{m}$
- $Z=1.5\text{m}$

Flow Map:
- Bubbly
- Slug
- Churn
- Annular
- Wispy-annular

[Diagram showing flow regimes and parameters]
Some Conclusions

- **Better Reactors Grow from Better Simulations**
  - I strongly believe this! 3D CFD results allow better understanding, more generality and fast prototyping

- **Mature Single Phase Applications**
  - The next step is “industrial robustness”
  - Users are not always as mature as the applications

- **Multiphase CFD is stepping up**
  - Already applied for design, successfully
  - Drastically enhanced robustness will derive from more physically based closures
  - High Quality CFD-grade Experimental Data are a unique asset to support Meso and Macro-scale modeling