Progress and Challenges in Predictive Thermal Hydraulic Simulations

Emilio Baglietto
A new approach to Nuclear Reactor Design

“...computational methods drive design”
“...computational methods drive design”

- Lumped parameter approaches are “still” the base for reactor design and licensing.
- 3-Dimensional “virtual reactor” models are necessary to reduce operating costs.
- 3-D TH phenomena can cause fatigue cracking, pipe deformations, and additionally lead to anticipated equipment failure.
- Developing a mitigation strategy requires understanding the mechanisms that lead to the failure: unsteady, 3-dimensional turbulent effects.
Extended range Twin Operations (ETOPS)
aka Engines Turning Or Passengers Swimming

Extensive use of Predictive Simulation have allowed granting of this ETOPS capability prior to the A350 entrance in service.
DOE Sponsored Programs

NEAMS provides support relevant to both reactor and fuel cycle R&D programs by creating analytic tools, codes and methods for use by scientists and engineers who need to simulate nuclear energy systems. NEAMS is developing a computational ToolKit which is comprised of both reactor and fuel systems analysis capabilities that can be exercised either coupled or independently, depending on the needs of the end user.

Aims to address key challenges of nuclear energy industry, through new M&S technology insights. CASL will deploy a technology step change (VERA) that supports today’s nuclear energy industry and accelerates future advances in the development of this cleaner energy source.

larger reliance on legacy physics codes early on the program, with selective development of new codes and models

includes the entire fuel cycle, as well as advanced reactors. Timeline is therefore a longer one, to support a larger, challenging and continuously evolving scope.
A snapshot of the DOE Tools

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REACTOR FUEL DESIGN APPLICATIONS
Fuel Applications 1: Press. Drops

Extensive validation/application

Mature Application

✓ Tools have greatly improved
✓ Models provide confidence (2006-2014)
✓ Trying to collect guidelines to stop re-inventing the wheel (at last)
Fuel Applications 1: Press. Drops
Application of ASME V&V20 to Predict Uncertainties in CFD Calc.

- First-of-kind calculation of uncertainties related to a CFD calculation for nuclear fuel application in the open literature \textit{with the ASME V&V20 method}
- CFD modeling to predict pressure losses in rod bundle is optimal
  - $E < U_{val}$: $E$ is lower than the upper limit of the possible error due to the CFD modeling assumptions and approximations
  - Modeling error within the "noise level" imposed by the numerical, input, and experimental uncertainties
- Improving the CFD modeling is not possible without an improvement on the numerical, geometric and experimental errors

Fuel Applications 2: Velocity predictions

Extensive (proprietary) validation/application

Mature Application

- Large validation experience
- Consistent Industrial Application
- Accuracy of experimental measurements is critical

\[ \sigma_{\text{PIV/CFD}}^2 = \sigma_{\text{CFD}}^2 + \sigma_{\text{PIV}}^2 \]

\[ \sigma_{\text{CFD, mean}} = 1\% \]

\[ \sigma_{\text{CFD, mean}} = 1.8\% \]

VALIDATION OF A CFD METHODOLOGY TO PREDICT FLOW FIELDS WITHIN ROD BUNDLES WITH SPACER GRIDS - C. Lascar et al.
Fuel Applications 3: consensus
Importance of mesh quality and turbulence modeling [nothing really new]

- Grid quality and consistency is “essential” for robust application [experience!, no tests!!]
- Importance of Anisotropic approach, based on physical representation
- Demonstrates improved prediction at all locations, including Turbulence Levels

![Diagram and equations related to turbulence modeling and mesh quality.]

RMS errors of the axial fluctuation velocities.

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Flow structures

Turbulent Jets

- Can you explain the GENX Chevrons??

- A jet nozzle has a sharp edge at which the flow separates. The fixed, circular separation line tends to impose axisymmetry on the initial large-scale eddies.
- Axisymmetry can be broken by corrugating the lip of the nozzle, which breaks up axisymmetric vortices into smaller, irregular eddies.

http://www.sussex.ac.uk/wcm/assets/media/7313/content/9161.250x193.jpg
Mass flow measurement by means of orifice plates

\[
q_m = C \frac{1}{4} \frac{d^2}{\sqrt{1}} \sqrt{2(p_1 - p_2)}
\]
Mass flow measurement by means of orifice plates: LES Results

Extruded 3D d 3D

Base size 2D d 3D

100% power level

80% power level

50% power level
CFD Activities in Support of Thermal-hydraulic Modeling of SFR Fuel Bundles

Emilio Baglietto, Joseph William Fricano, Eugeny Sosnovsky

NSE
Nuclear Science & Engineering at MIT
science : systems : society
Model Geometry

- Modeling inlet region of the test section shown to be important
In-Bundle Comparison (2014)

- Compare to 36 different thermocouples for each case
  - Plot below shows the experimental measurement for each thermocouple matches the at least one of the CFD probes
- Analyzed the complete data set
  - CDF of all the error of the measurement and nearest probe for all data points for all 7 cases
Distorted fuel analysis
(Left: Nominal geometry; Right: Deformed geometry)
**Irradiation-caused Deformation Consequences (coolant)**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pressure drop</td>
<td>-2.04%</td>
</tr>
<tr>
<td>Hot channel outlet temperature</td>
<td>+6.99K</td>
</tr>
<tr>
<td>Average mass crossflux</td>
<td>-11.4%</td>
</tr>
<tr>
<td>Sodium temperature penalty factor</td>
<td>1.058</td>
</tr>
</tbody>
</table>

*The sodium temperature penalty factor is:*  
“The ratio of the hottest subchannel’s outlet temperature increase to the nominal difference between this subchannel’s inlet and outlet temperatures.”
Multiphase CFD

... the grand challenge
A CASL-centric view

With contributions from:
Mark Christon (LANL) – Area Lead
Igor Bolotnov (NCSU)
Gretar Tryggvason (ND)
Jacopo Buongiorno (MIT)
Yassin Hassan (TAMU)
Nam Dinh (NCSU)
Mike Podowski (RPI)
Annalisa Manera (UM)
Good news: mature baseline

- CASL Validation has Demonstrated Maturity of Closures
- Demonstrated Portability of Closures (STAR-CCM+)
- The DEBORA Test Case Results are shown below
Demonstration of GEN-I M-CFD Closure for onset of DNB

- **Industrial Application has demonstrated:**
  - Usability of GEN-1 Closure up to onset of DNB
  - Good trend predictions
  - Good generality

- **Ongoing work is looking at:**
  - Extended generality via more realistic mechanistic representation
  - Extension to oxidized/crudedd surface
  - Incorporating realistic DNB Mechanism

**Large HQ database**

Jin Yan - ISACC-2013, Xian, China
GEN-II Heat Partitioning: Improved Physical Understanding

Key challenges/approach:
Tremendously complex surface interactions, cannot be resolved by first principle:

- Selection of local characteristic in the CFD solution to drive the SGS Model representation
- Fully Mechanistic representation to extend generality and allow leveraging experimental microscale measurements
- Tracking of subgrid surface characteristics to:
  - Include influence of surface evolution (oxidation, crud, etc.)
  - Extension to CHF description as surface hydrodynamic phenomenon

- Mechanistic model proposed by Judd and Hwang (1976)
- Adapted by Kurul and Podowski (1990) for wall heat flux partitioning during pool nucleate boiling.
- While limited it is de-facto the only model in M-CFD.
- Erroneous representation of physical boiling.
GEN-II Heat Partitioning: Quick Overview

1. Mechanistic Representation of Bubble Lift off and Departure Diameters

2. Accurate evaluation of evaporation heat flux by modeling effective microlayer

3. Account for sliding bubble effect on heat transfer and nucleation sites

4. Account surface quenching after bubble departure

5. Account for bubble interaction on surface
GEN-II Heat Partitioning: assessment

- Validation performed against MIT boiling curves
- Allows validating separate model components
- Calibration-free—demonstrated generality deriving from improved physical representation

Evaporation term is not dominant contribution
- Effect of bubble sliding dominates Flow Boiling Heat Transfer (previously postulated by Basu)
- The new model demonstrates improved predictions at all conditions
- Enhanced robustness at higher heat fluxes

Bucci, Su, 2015

\[ q''(x, y, t) = q''_{lto}(t) - q''_s(x, y, t) \]
Tackling the grand-challenge: CHF

- Bubbles merge on heater surface prior to departure
  - Indicates size of dry surface patches

\[ N_b'' = f t_g N'' \]

\[ P = 1 - e^{-N_b'' \pi D_d^2} \]

complete spatial randomness methods (CSR)

- I can track the wet and dry surface in a “cell”
  - This allows me to split the heat transfer into 2 components where

\[ q''_{tot} = A_{dry} q''_{vapor\_film} + (1 - A_{dry})q''_{Nucleate} \]

.. as the heat flux increases, heat removed by the wetted area can’t keep up, leading to larger coalescence between bubbles, and further decreases in wetted area, resulting in surface dryout.