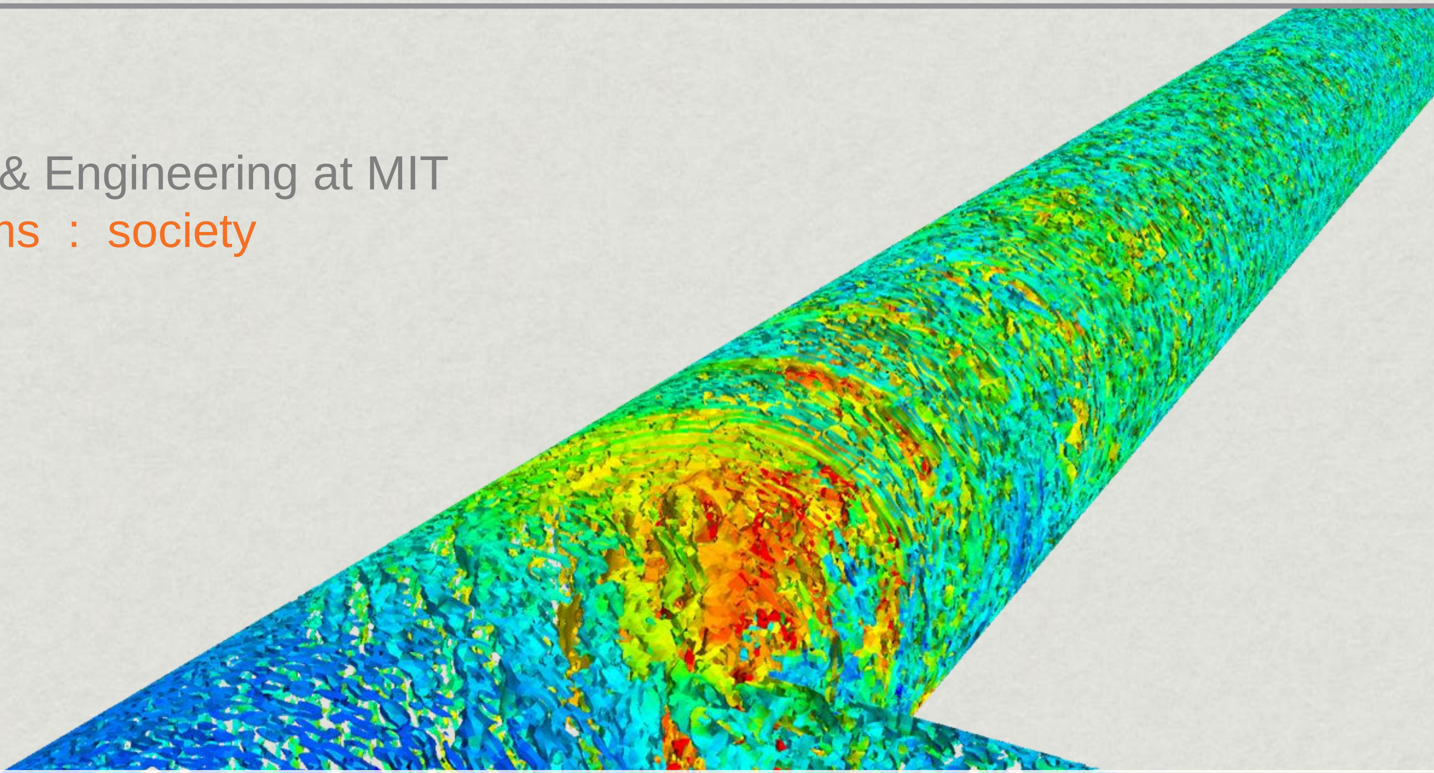


NSE

Nuclear Science & Engineering at MIT

science : systems : society

Politecnico di Milano - Friday, May 17, 2013

Novel experimental and CFD analysis of two-phase flow in support of reactor safety

Emilio Baglietto

Massachusetts Institute of Technology

CFD Modeling of Multiphase Flow

There is no generally applicable model, but models are driven by needs and limitations:

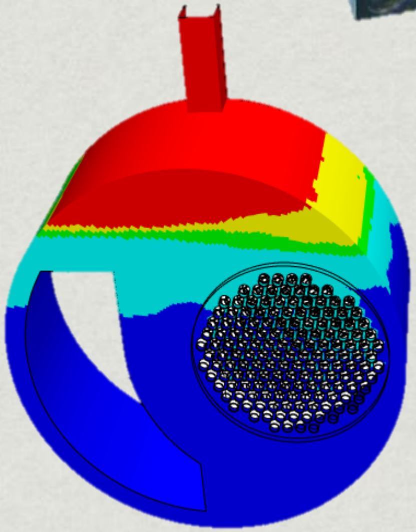
- **Flow characteristics**
  - ✓ Bubbly slug
  - ✓ Annular
  - ✓ Droplets
- **Process characteristics**
  - ✓ Separation
  - ✓ Boiling
  - ✓ Mixing
- **Parameter of interest**
  - ✓ Void Fraction
  - ✓ Wall temperatures

An important distinction

- Computational fluid dynamics *as a research tool* for multi-phase flows.

www.nd.edu

- Computational fluid dynamics *as a design tool* for multi-phase flows

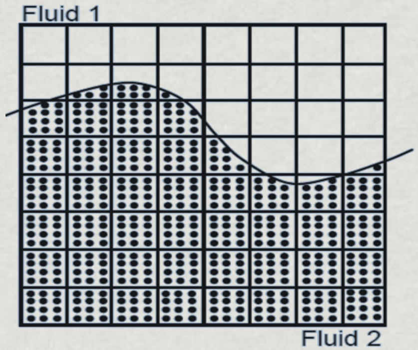


MULTIPHASE CFD (M-CFD) METHODS

- **Lagrangian (Eulerian/Lagrangian)**
  – Track individual point particles.
  – Particles do not interact.
- **Discrete element method (DEM)**
  – Solve the trajectories of individual objects and their collisions, inside a continuous phase.
- **Homogeneous 2-P**
  – Dispersed phase in a continuous phase.
  – Solve one momentum equation for the mixture.
- **Eulerian Multiphase (Eulerian/Eulerian)**
  – Solve as many momentum equations as there are phases.
- **Interface Tracking/Capturing (ITM)**
  – Requires capturing the sharp interface, resolving the 2-P flow structures.

Markers in Fluid Particle Method

- Marker and Cell (MAC) method - Harlow and Welch (1965).
- One of the earliest methods to resolve free surface problems.
- Based on Eulerian mesh of control volumes, massless markers are transported in a Lagrangian fashion to distinguish between fluids.



Fluids are marked with massless markers

One of the most significant and commonly requested areas of real world simulation is fluid simulation.

MAC Method used for 'X-Men: First Class'

Front Tracking Method

- **Unverdi and Tryggvason (1992) introduced the Front Tracking Method**
- The Lagrangian interface is represented by a set of connected line segments, and is explicitly tracked and used to reconstruct a representation of the fluid property fields on an Eulerian mesh.
- Most successful method for DNS of bubbly flow

www.nd.edu

The "leap" for M-CFD:
"Safety analysis applications"

MESO-SCALE Representation of Multi-phase Flow

- While first principle representation of Multiphase Flow [quasi-DNS] is possible for specific limited simulations domains we must assemble a practical, robust, engineering approach to M-CFD.

- ***The challenge is to capture the dominant characteristics of the flow physics and to represent them with adequate and efficient models.***

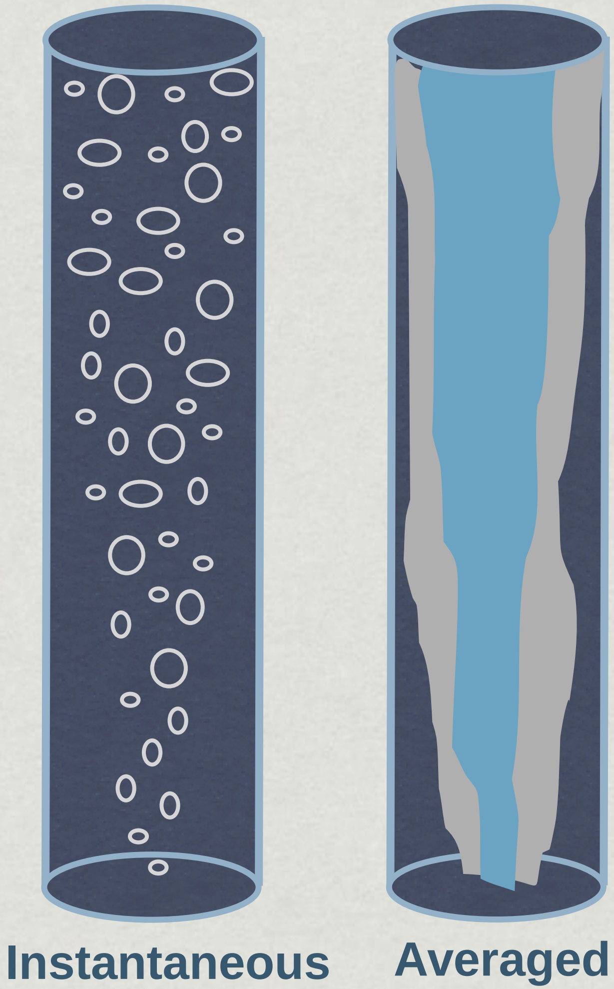
- The framework is the two fluid model representation (aka EMP, 6-eq model…)

MESO-SCALE “Interpenetrating continua”

- We consider the phases are mixed on length scales smaller than we wish to resolve and can be treated as continuous fluids.

- Both phases coexist everywhere, this concept is called “Interpenetrating continua”.

- Requires “Closure” to recover the information loss in the “Interpenetrating” assumption.



Conservation of mass

- Conservation of mass for phase k is:

$$\frac{\partial}{\partial t}\left(\alpha_k \rho_k\right) + \nabla.\left(\alpha_k \rho_k u_k\right) = \sum_{j=1}^{N}\left(\dot{m}_{jk} - \dot{m}_{kj}\right)$$

  - α=volume fraction, ρ=density, u=velocity,
  - N=total number of phases, $\dot{m}$=mass transfer rate.

- Sum of volume fraction is unity,

$$\sum_k \alpha_k = 1$$

Conservation of momentum

- Conservation of momentum for phase k is:

$$\frac{\partial}{\partial t}(\alpha_k \rho_k u_k) + \nabla.(\alpha_k \rho_k u_k u_k)$$

$$= -\alpha_k \nabla p + \alpha_k \rho_k g + \nabla.\alpha_k (\tau_k + \tau_k{}^t) + M_k$$

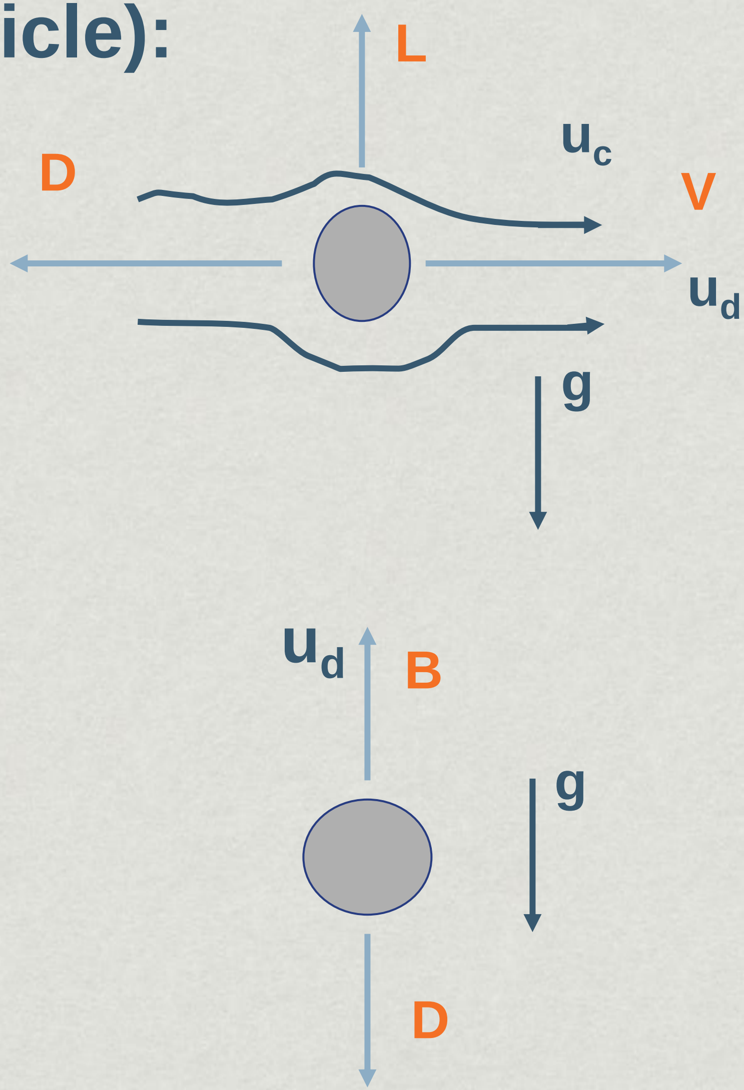
- *p* = pressure,
- M = sum of interfacial forces (drag, turbulence drag, lift, virtual mass) and momentum transfer associated with mass transfer.

$$M = F_D + F_{TD} + F_L + F_{VM} + \sum_{j=1}^{N} \left(\dot{m}_{jk} u_j - \dot{m}_{kj} u_k \right)$$

M = sum of interfacial forces (drag, turbulence drag, lift, virtual mass) and momentum transfer associated with mass transfer.

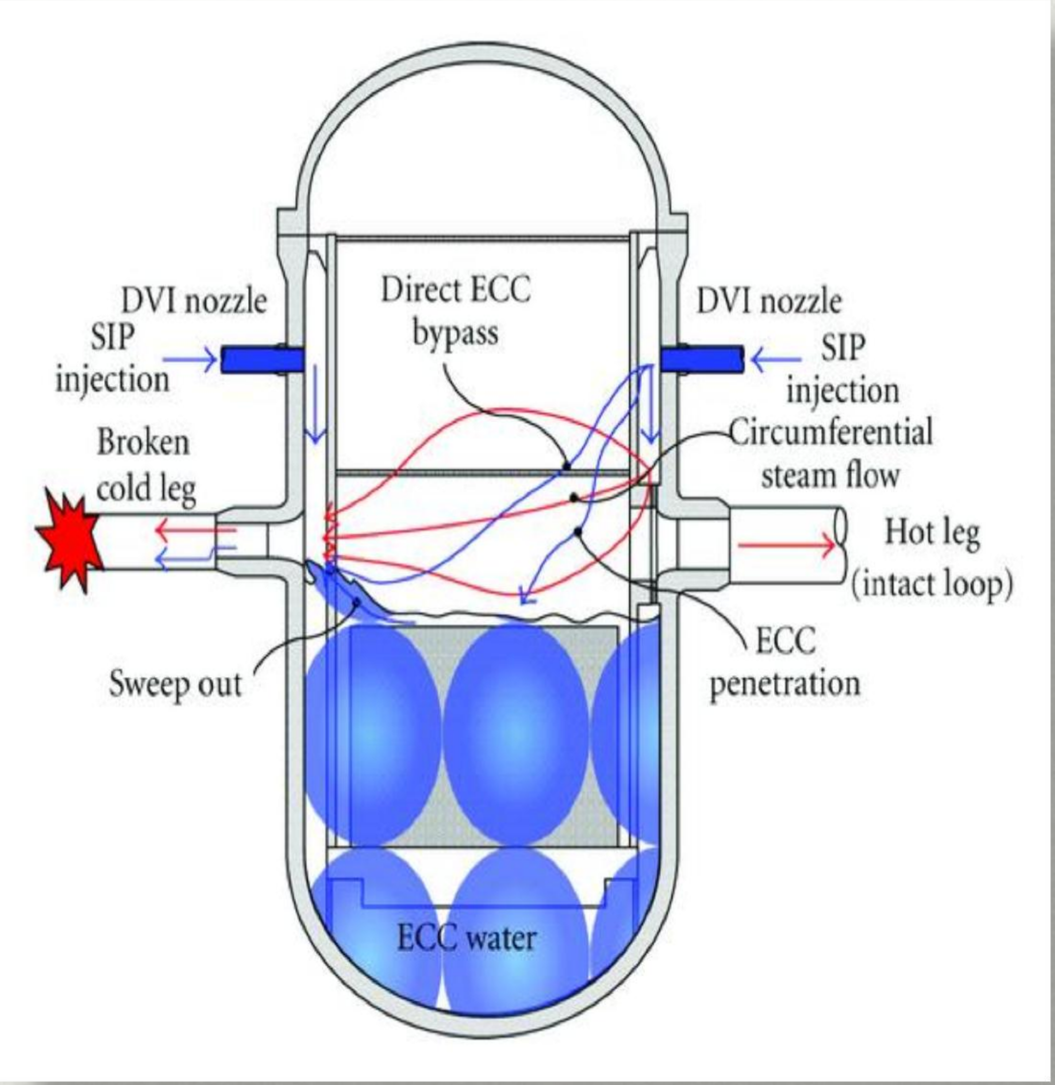
▪ Interfacial forces (on a particle):

- Buoyancy, B.
- Viscous Drag, D.
- Lateral Lift, L.
- Virtual mass, V.
- Basset force.
- Turbulence Dispersion.
- Wall Lubrication.
- …



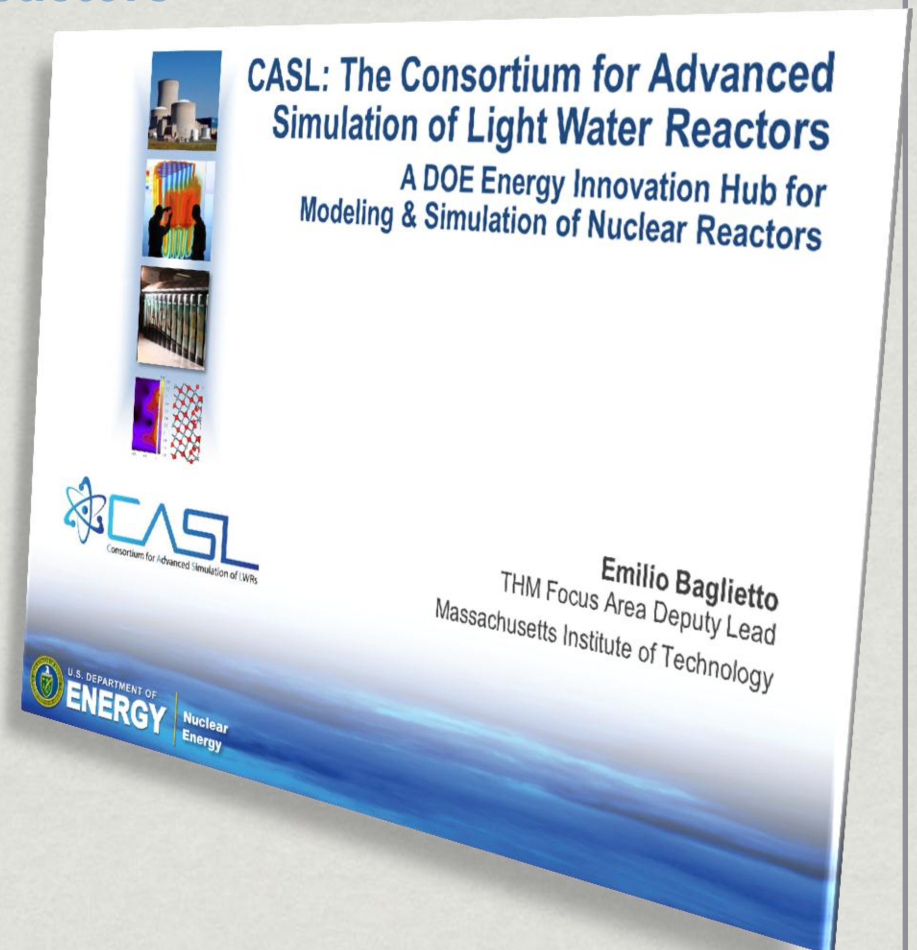
Why do we need Multiphase-CFD ??

A schematic diagram of the direct ECC bypass.



CASL: The Consortium for Advanced Simulation of Light Water Reactors

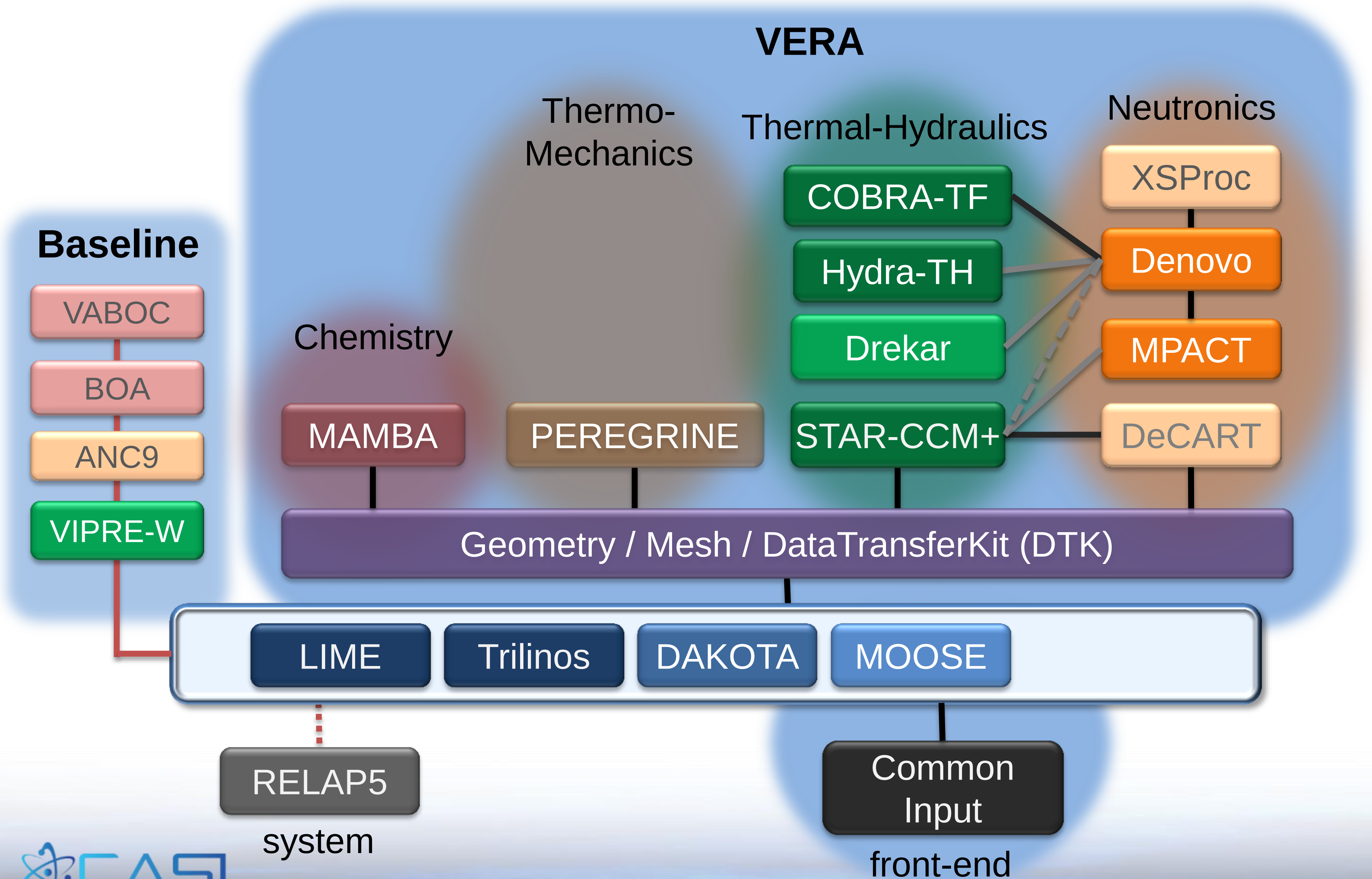
A DOE Energy Innovation Hub for Modeling & Simulation of Nuclear Reactors



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



MIT Team

Advanced M-CFD

Prof. Emilio Baglietto

Lindsey Gilman (PhD student)

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.

Boiling Model Development

Rosie Sugrue (graduate student)

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

Momentum Closures

Prof. Jacopo Buongiorno

Dr. Thomas McKrell (research scientist)

Bren Phillips (PhD student)

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

Dedicated Experimental Database

Dr. Gustavo Rabello (post-doc)

Alexandre Guion (graduate student)

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.

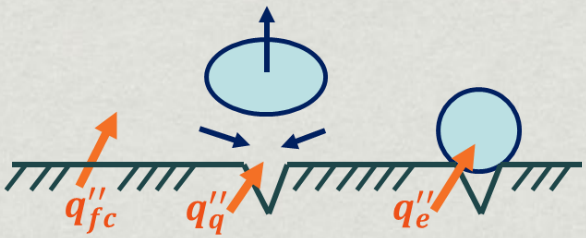
DNS/ITM Database

Novel Mechanistic Flow Boiling Model

Kurul and Podowski Partitioning

$$q''_{tot} = q''_{fc} + q''_{q} + q''_{e}$$

Convective Quenching Evaporation

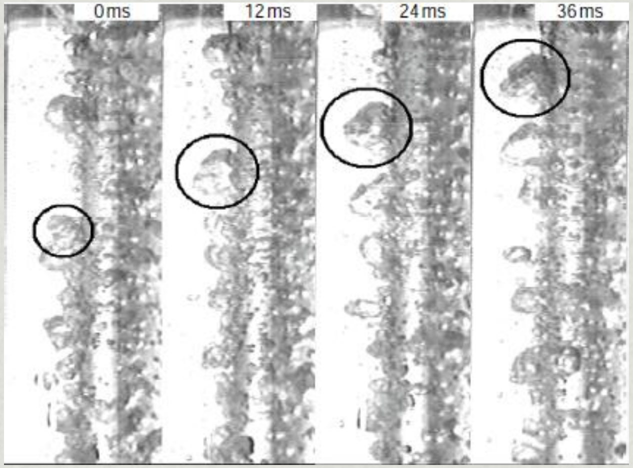


Mechanistic approach

- *Flexible model*
- *Proven application record*
- *First deployment option for Hydra-TH*

So why a new model? *(hopefully start addressing Nam's fundamental question)*

- I will go through this "one piece at a time", but first things first, the final target:
- *Increased synergy with experimental "micro" measurements*
- *Extended applicability (lower/ higher vapor generation)*
- *Include modeling toward limiting behavior (CHF)*

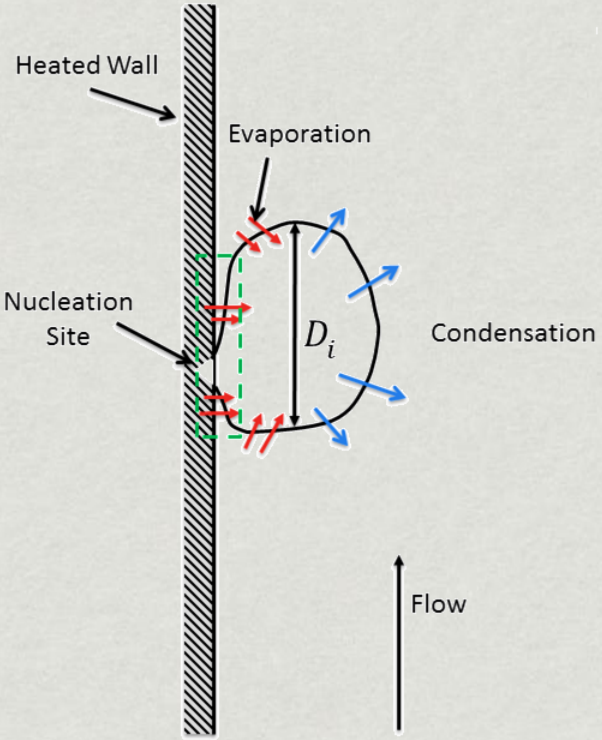


Novel Mechanistic Flow Boiling Model (2)

Key Components - 1

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***



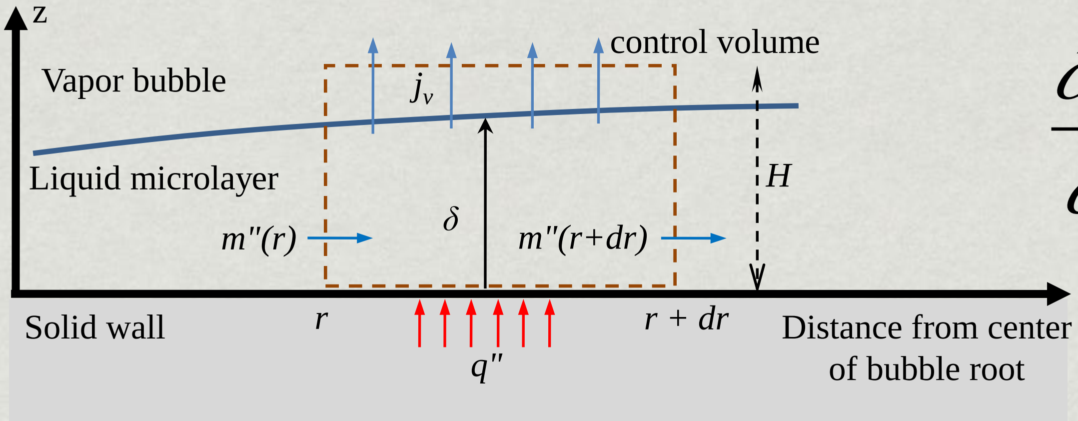
$$q''_e = \rho_v \cancel{h_{fg} \frac{\pi}{6}} D_d^3 N'' f \propto S_{microlayer}$$

Need to model the microlayer evaporation – *leverage ITM_DNS*

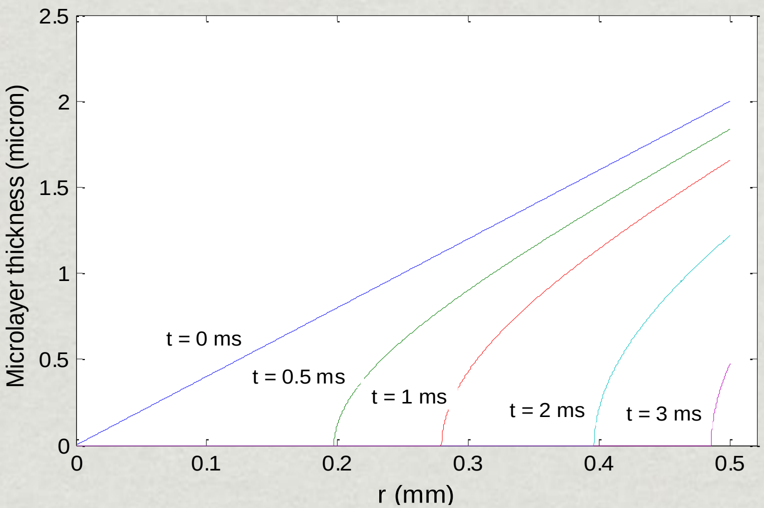
Microlayer Model

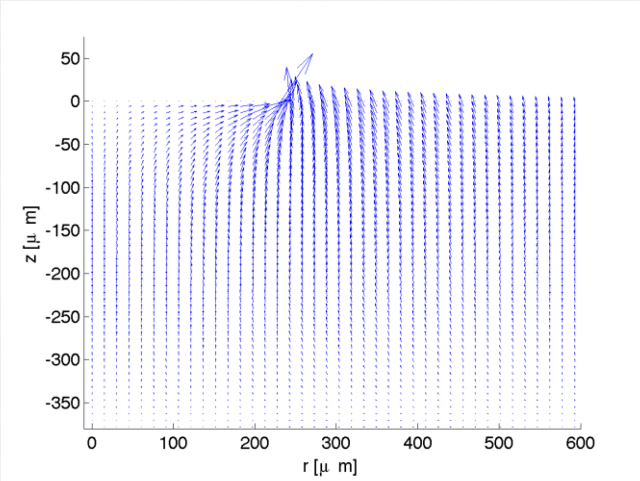
Rosie Sugrue, Alex Guion,
Gustavo Rabello

Axisymmetric, time-dependent model:



$$\frac{\partial \delta}{\partial t} = -\frac{k_l (T_w - T_{sat})}{\delta \rho_f h_{fg}}$$





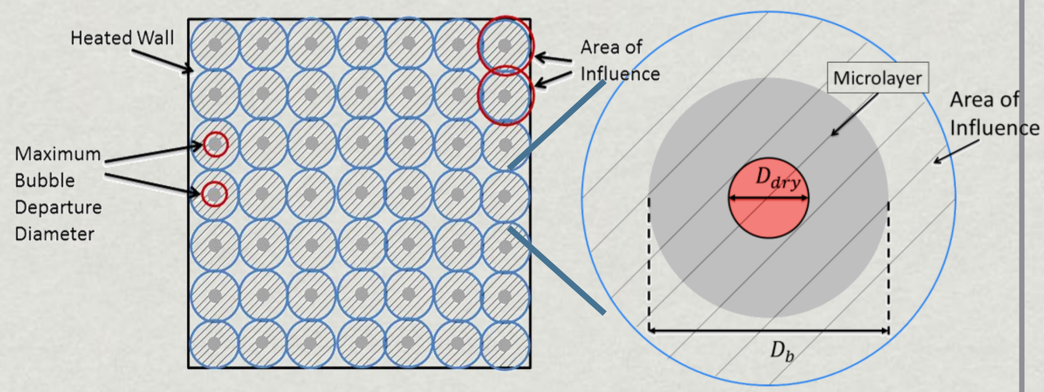
Model predicts time evolution of microlayer shape + heat flux associated with microlayer evaporation

Novel Mechanistic Flow Boiling Model (3)

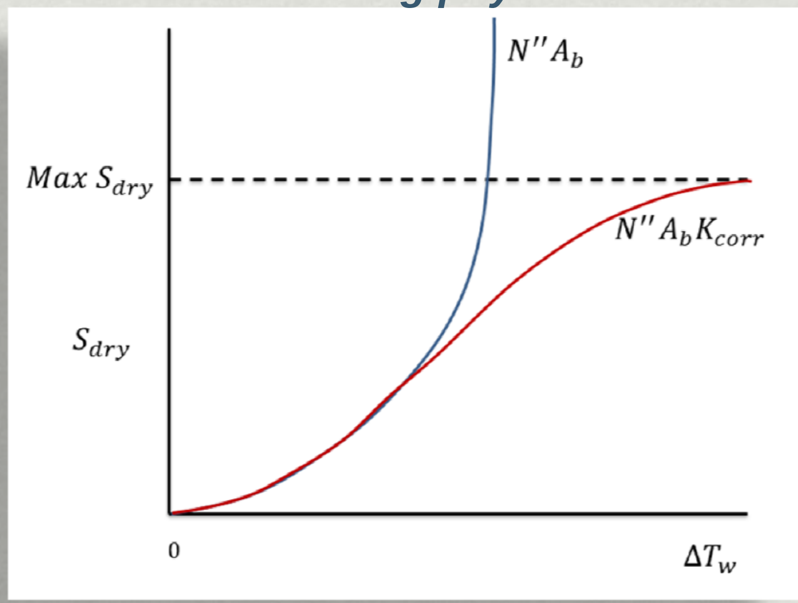
Key Components - 2

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***

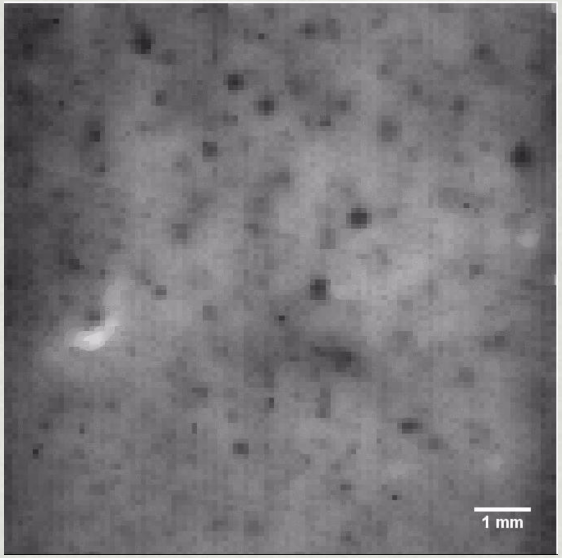


Nucleation Site Density

Bren Phillips, Rosie Sugrue,
Tom McKrell

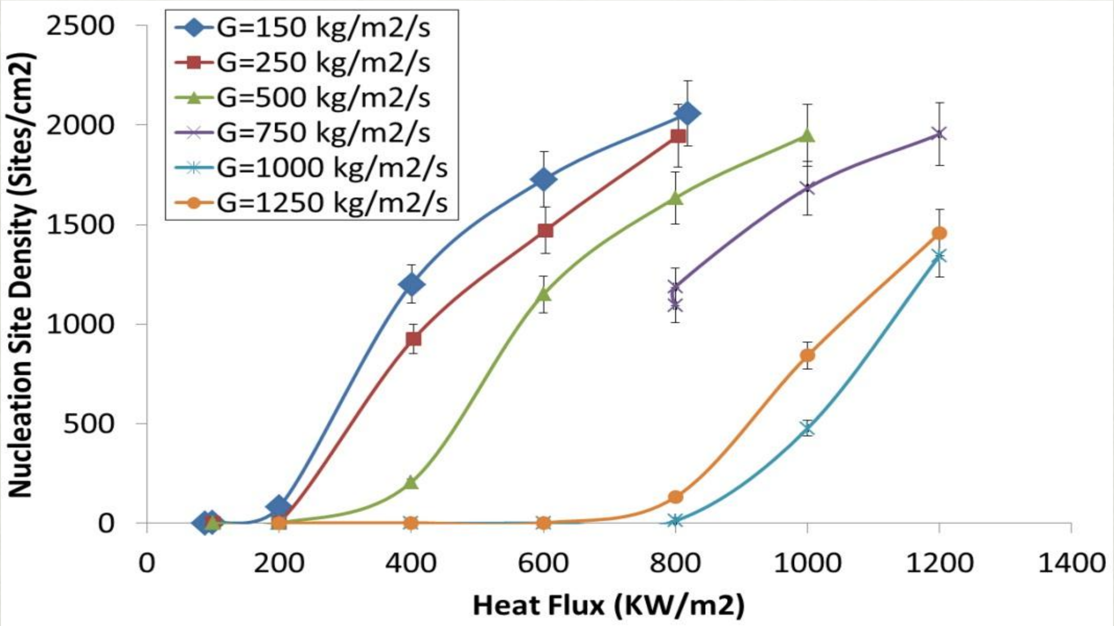
(hope to leverage as validation rather than calibration)

- Automated routine for counting nucleation sites from IR data
- Verified with manual counting
- Currently investigating statistical correction for measurement resolution



Data follow expected trends with heat and mass flux

Note plateauing at high heat flux

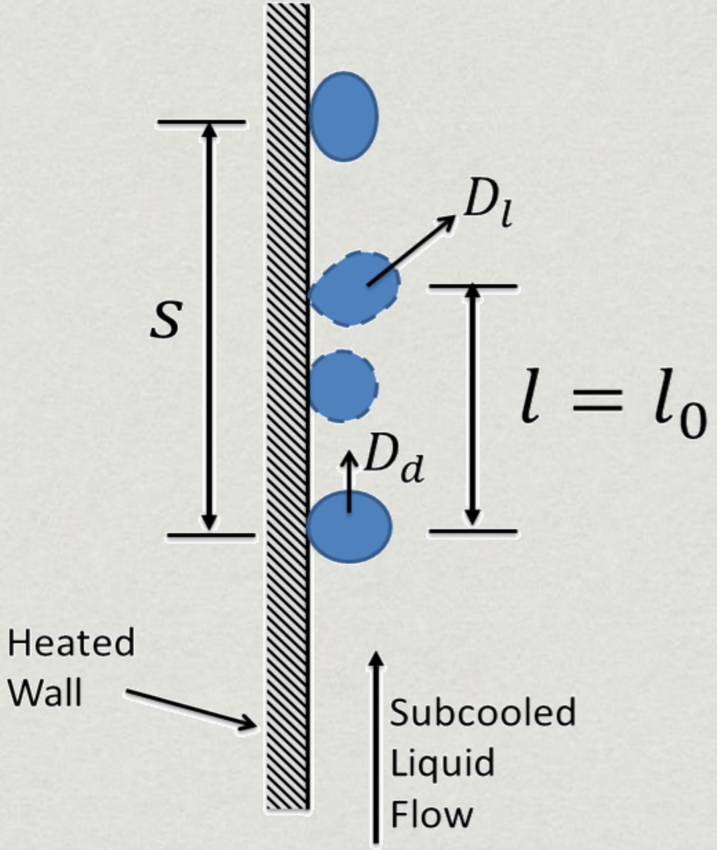


Novel Mechanistic Flow Boiling Model (4)

Key Components - 3

Bubble departure and sliding - I

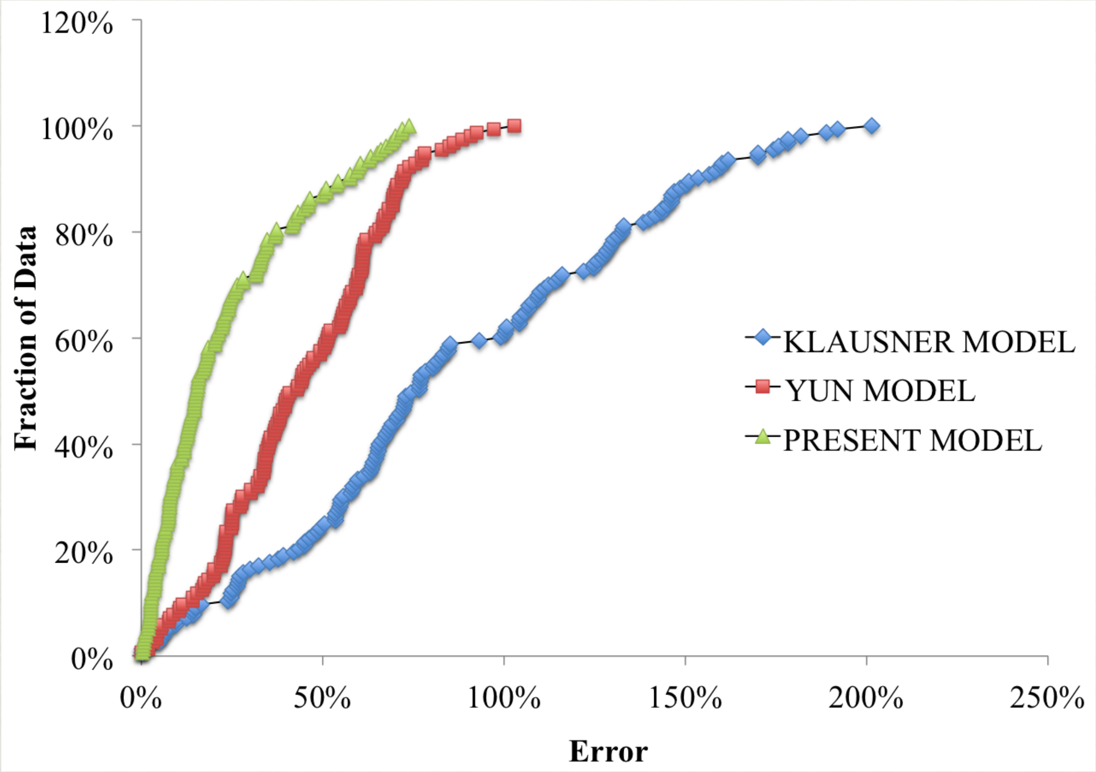
- *Leverage improved mechanistic force balance model a la Klausner:*
  - ✓ Sugrue, Buongiorno 2013
- *MIT implementation shared among CASL partners (external C routine)*
- *Optimal estimation of departure diameter (D_d)*
- *Allows quantifying lift off diameter (D_l)*
- *Includes wall inclination effects*



Bubble Departure Diameter Model

Bren Phillips, Rosie Sugrue, Tom McKrell

Prediction statistics for present model are much better than Klausner's original model and Yun's modified model



Aggregate Errors[1]:

Klausner Model: 85.5% (σ=49.7%)

Yun Model: 43.9% (σ=23.1%)

Present Model: 22.4% (σ=19.9%)

[1]Errors across experimental databases of Klausner et al., Sugrue et al., Zeng et al., Prodanovic et al., and Situ et al.

A CFD Implementation

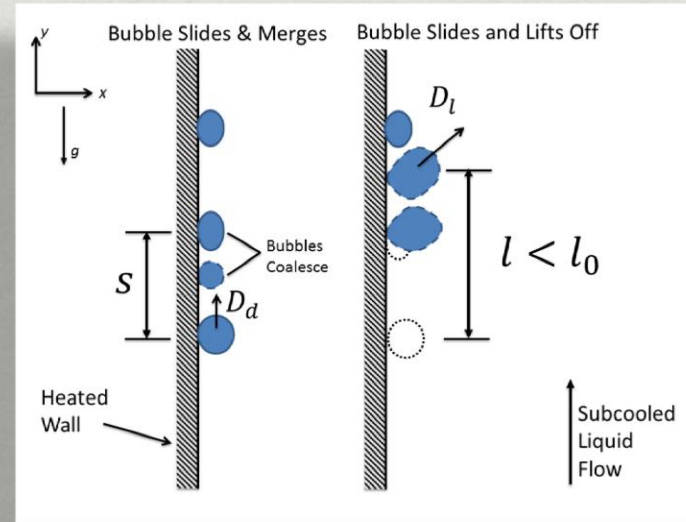
- Improved Mechanistic Departure Model fundamental component for all partitioning models.
- First Implementation an testing priority.
- Currently being tested
- Subroutine written in C
- Linked to STAR-CCM+ by building a user code library
- Employs multiple field functions available in STAR-CCM+, but fully commented for quick adaptability

ucfbmodels.c

```c
/* ---------------------------------------------------------------------------
 * ucmodels.c: implementation for shareable application-specific ucode models
 * ---------------------------------------------------------------------------
 */

#include <math.h>
#include <stdio.h>
#include "ucfbmodels.h"

/****************************************************************************
 * userBubbleDiameter(bubbleVolumeFraction).
 ***************************************************************************/

void userBubbleDiameter(
  Real*         result,
  int           size,
  Real*         DensityLiquid,
  Real*         DensityVapor,
  Real*         DynamicViscosityLiquid,
  Real*         UstarLiquid,
  Real*         Pr,
  Real*         SpecificHeatLiquid,
  Real*         ThermalDiffusivity,
  Real*         BoundaryHeatFluxLiquid,
  Real*         dU_dy,
  Real*         theta,
  Real*         ThermalConductivityLiquid
) {

  /* [0] declarations */
// Defining Constants in the Bubble Departure Model //

// Surface Tension Force //

double pi       =       3.14159;                // Defining the constant pi; This may already be defined in C by using "PI" //
 double alpha   = 90.63*(pi/180);  // Advancing contact angle in Rosie's Experiment [rad] //
double beta =   8.03*(pi/180);  // Receding contact angle in Rosie's Experiment [rad] //
double sigma = 0.058988; // Surface Tension Defined here because it's field function looks strange

// Buoyancy Force //

double g =              9.81; // Gravitational Constant [m/s^2] //


// Quasi-Steady Drag Force //

double Kappa = 0.4;   // Constant provided by Klausner //
double Chi =    11;       // Constant Provided by Klausner //
double c =              7.4;  // Constant Provided by Klausner //
double n =              0.65; // Constant Provided by Klausner //

// Unsteady Force //
```

Novel Mechanistic Flow Boiling Model (5)

Key Components - 3

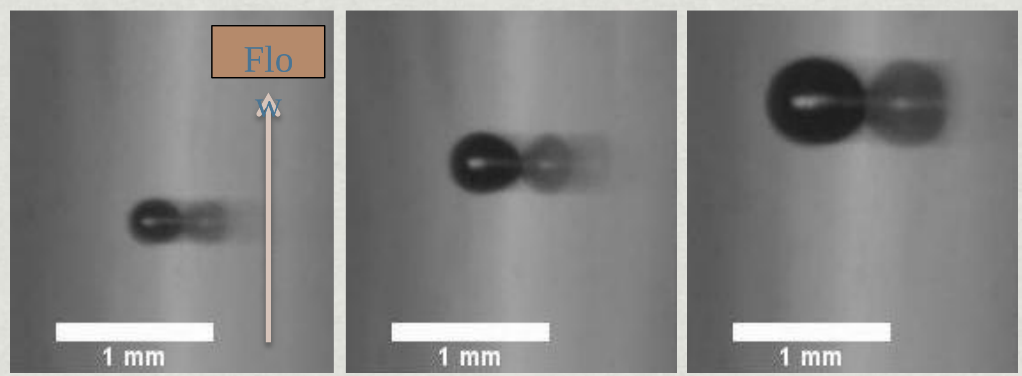


Bubble departure and sliding (and coalescence)

Not included in K-P model

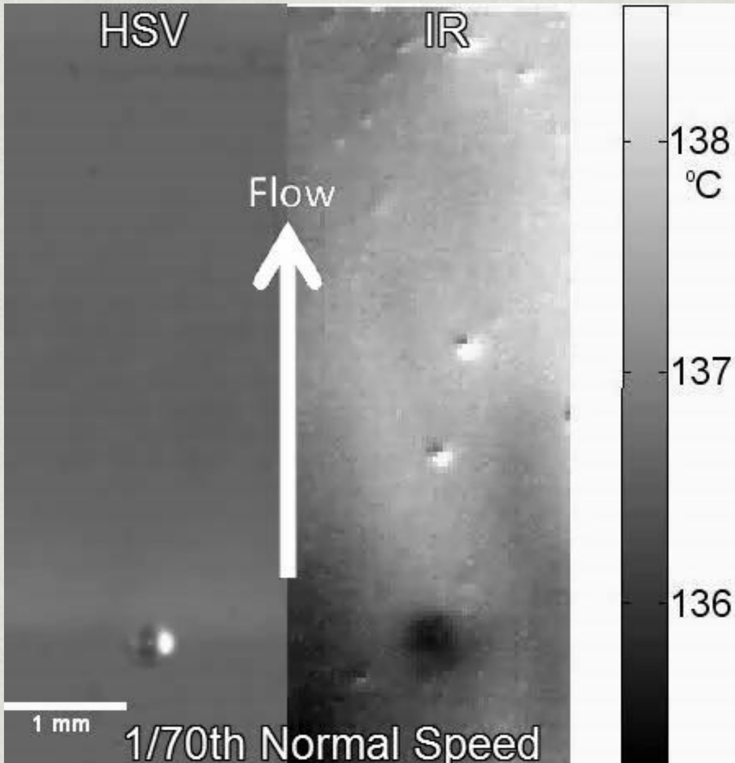
Transient conduction: q''_{tc}

- *Active in areas swept by bubbles.*
- *Conduction through thin liquid film*
- *(experiment to confirm area of influence)*
- *"Local cooling roughly independent of mass flux"*
- *Mass flux enters in the "average area swept by bubbles*
- *Captured using enhancement factor dependent on number of bubbles and time over which the transient conduction mode occurs.*



Sliding Bubbles in Subcooled Flow Boiling

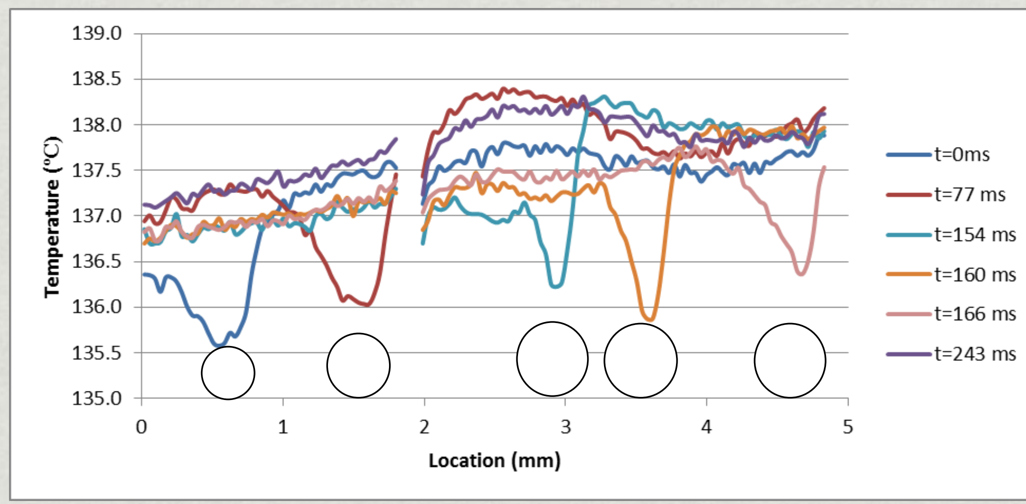
Bren Phillips, Rosie Sugrue, Tom McKrell



$$P = 1\,atm, q'' = 130\ \frac{kW}{m^2},$$

$$G = 200\ \frac{kg}{m^2 s}, \Delta T_{sub} = 10\ °C$$

Synched IR and HSV allow measurement of sliding bubble velocity and local cooling



Novel Mechanistic Flow Boiling Model (6)

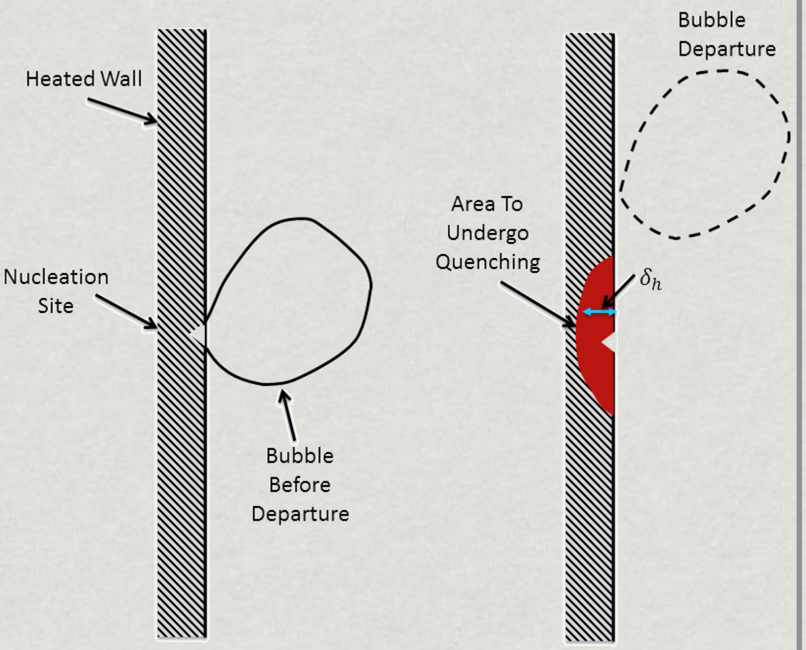
Key Components - 4

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*



$$q''_q = \rho_h c_{p,h}(T_a - T_w)\delta_h$$

Novel Mechanistic Flow Boiling Model (7)

Key Components – 5

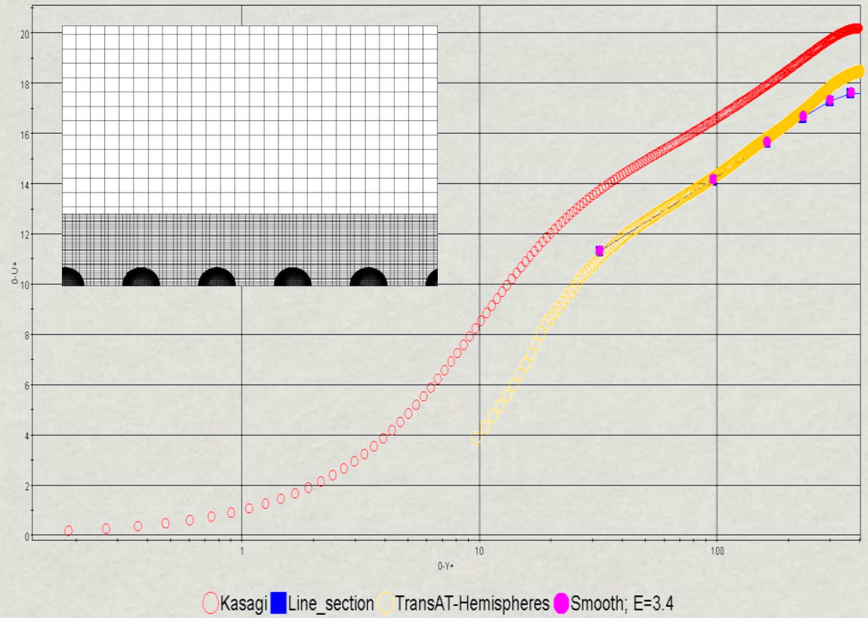
Law of the "boiling" wall

- *Forced convection should be modified to account for presence of bubble (growing, sliding, departing)*
- *Common component to all CASL models*

Generalized correction

- *Implement a "bubble aware" set of wall functions, for V, T, K*
- *Start from DNS results from ITM-1*
- *Final corrections will require:*
  - ✓ MIT and TAMU experiments
  - ✓ ND and NCSU ITM/DNS

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



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* → *???*

$$\underbrace{\hspace{20em}}$$

Subcooled Boiling Curves

Subcooled Boiling Curves and Heat Transfer Coefficient

Bren Phillips, Rosie Sugrue, Tom McKrell

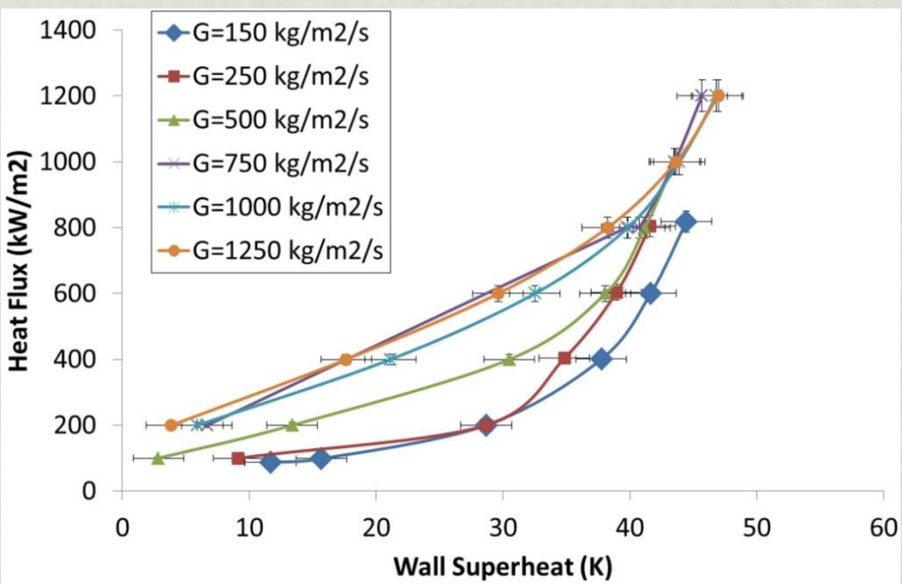
First data collected at:

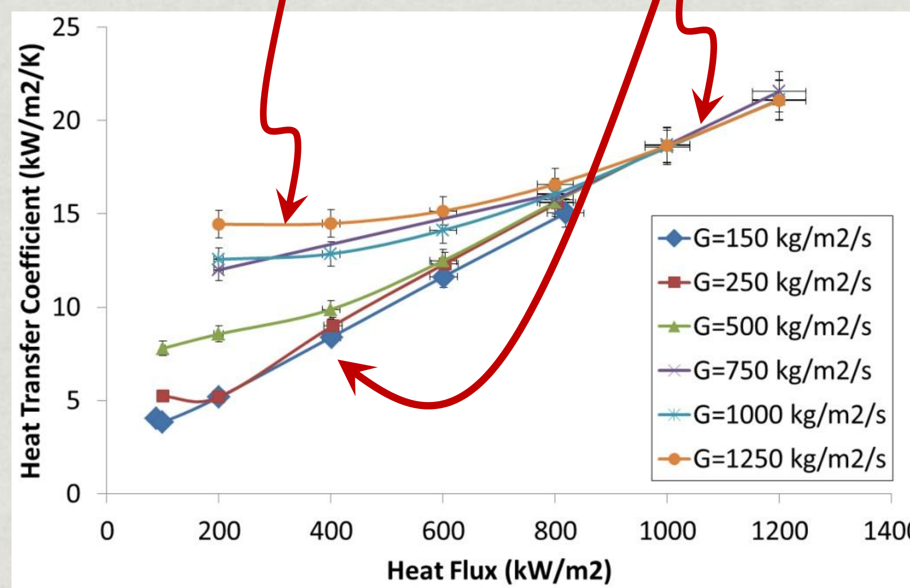
- $q'' = 0\text{–}1300$ kW/m^2
- $\Delta T_{sub} = 10^{o}$C
- G = 150–1250 kg/m^{2}s
- P = 0.101 MPa

Data follow all expected trends

Fully-developed nucleate boiling

Forced convection





Subcooled Boiling Curves and Heat Transfer Coefficient

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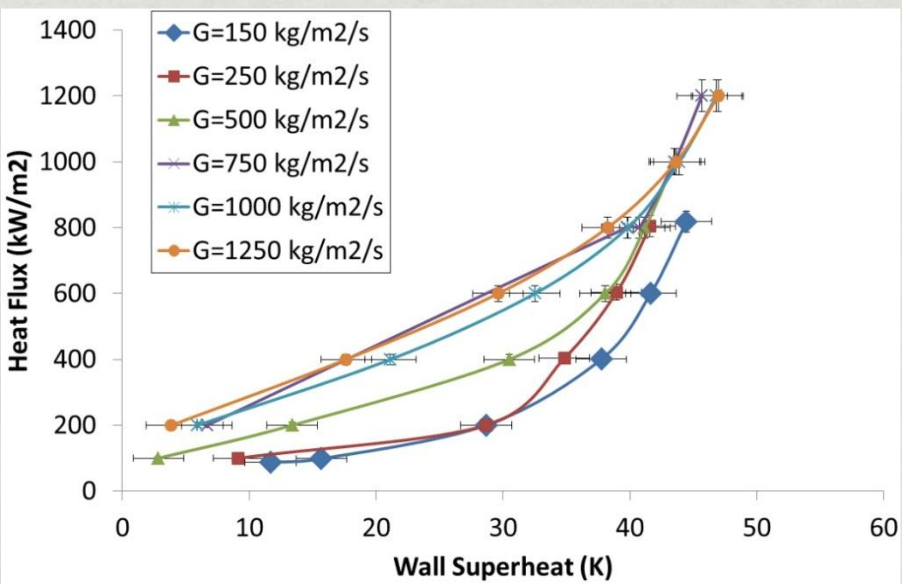
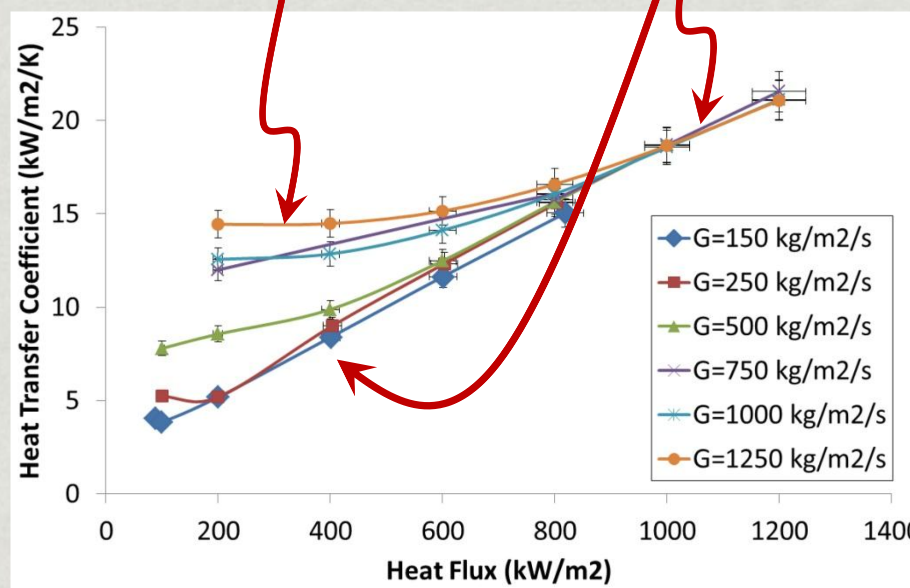
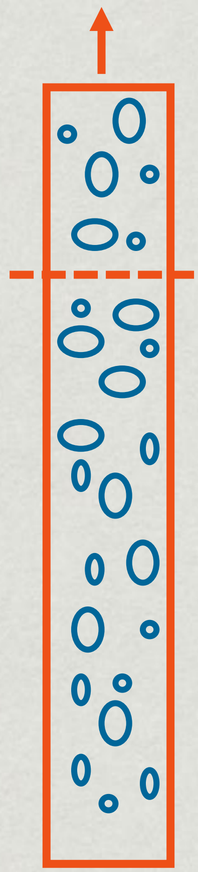


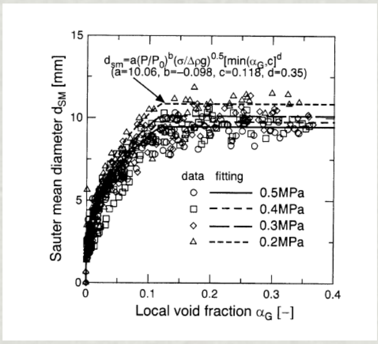


Quickly … on momentum closure

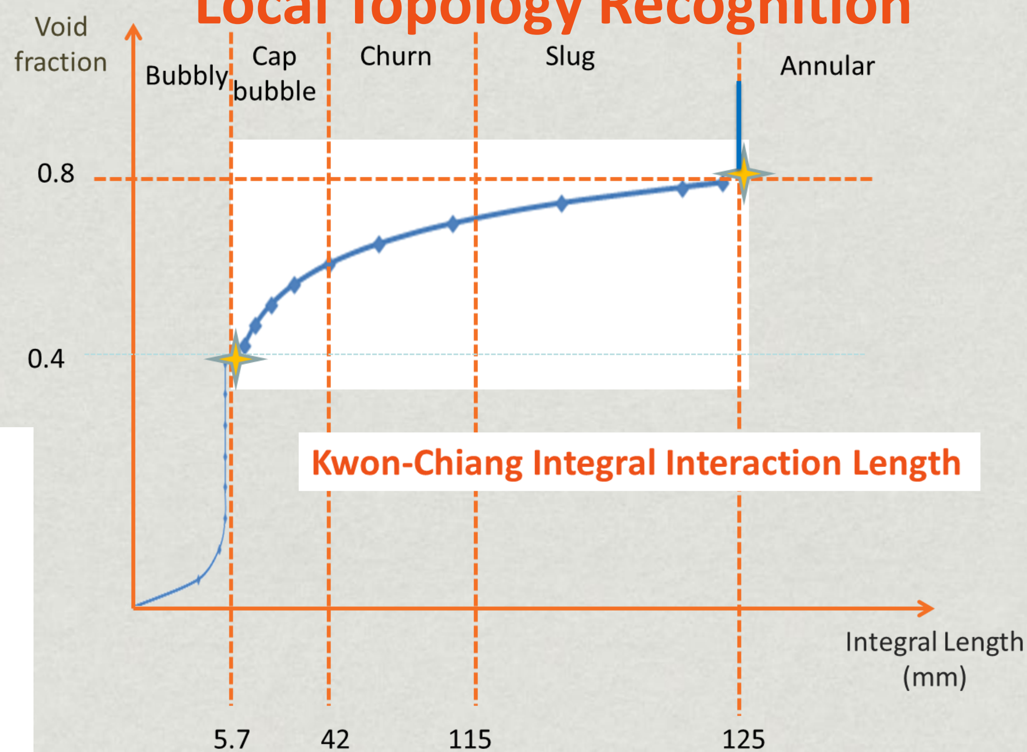
- We need a robust closure formulation for extended application
- *Robust* requires realistic physics, don't always blame the code
- The general approach requires a physical under-relaxation (which is simply physics) a homework example:

Each region adopts specific Lift and Drag Formulations (continuous)

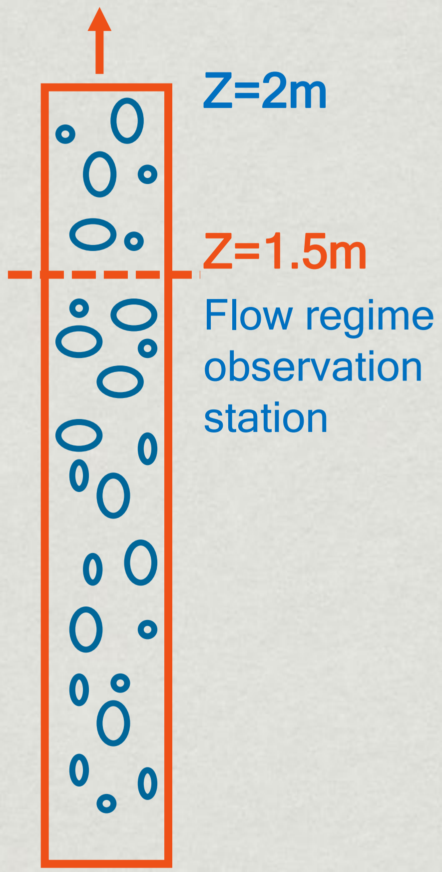


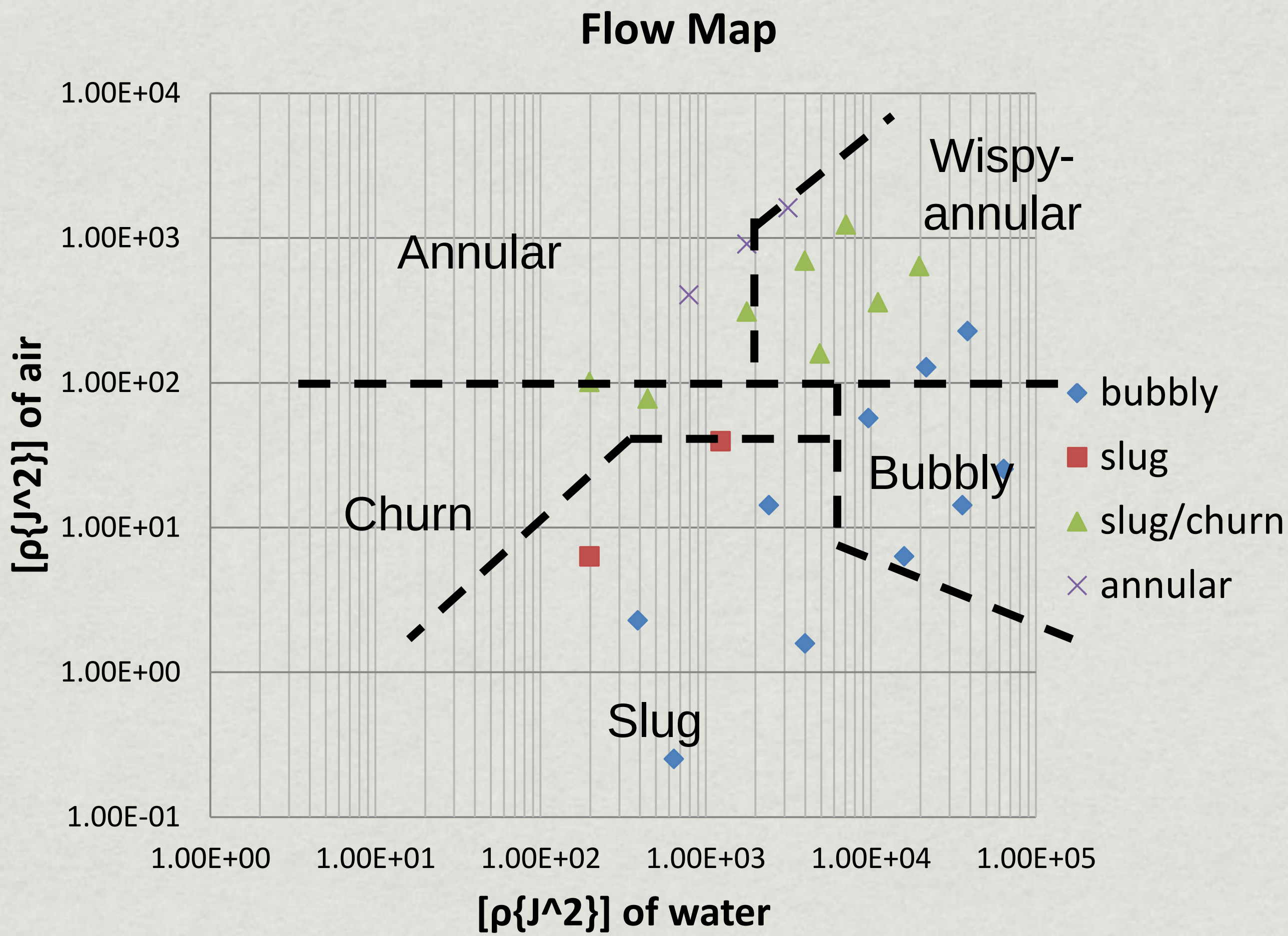


Local Topology Recognition



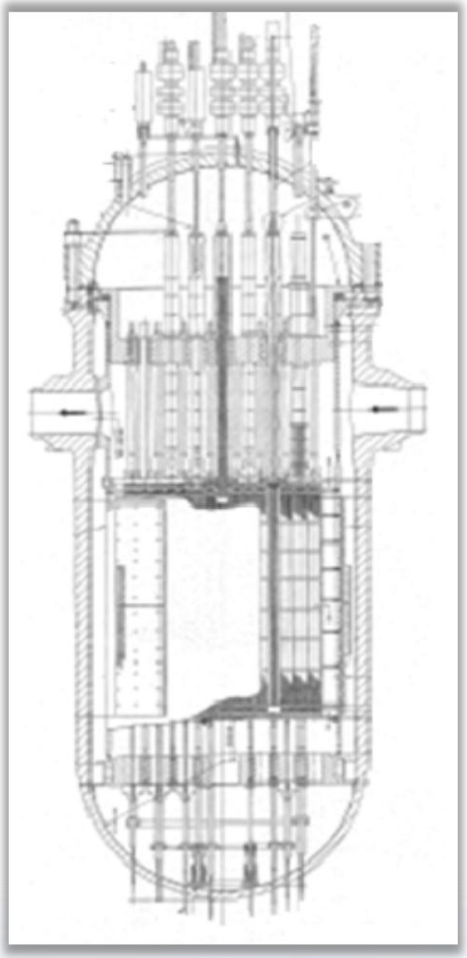
Why physics based ??



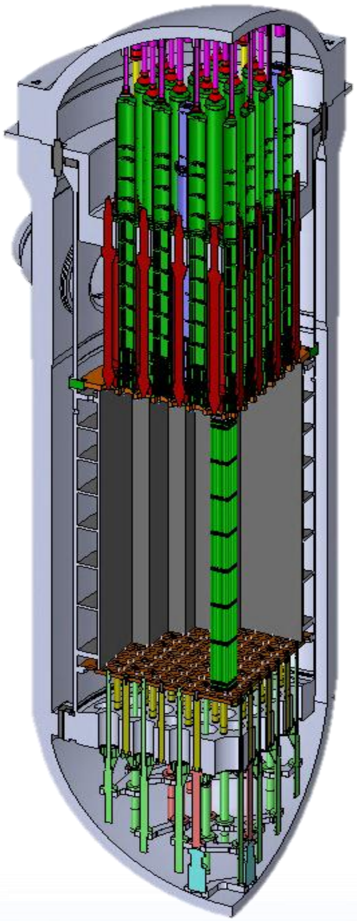


4-Loop Westinghouse PWR Multi-Physics Model Development

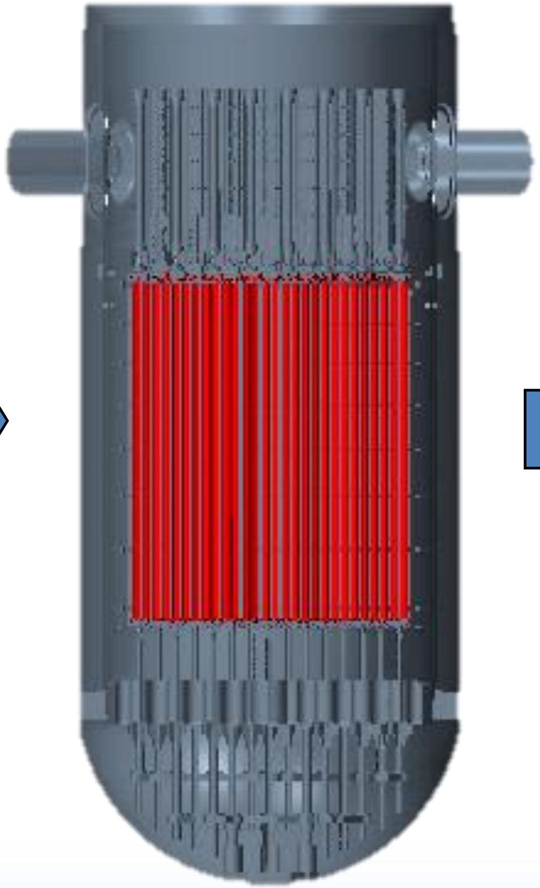
- RPV ID 173”, 193/4 Fuel Assemblies,13,944 fuel rods (fuel pellets, helium gap), 434 spacers, 148,224 mixing vanes; 1.2 billion cells



Drawings



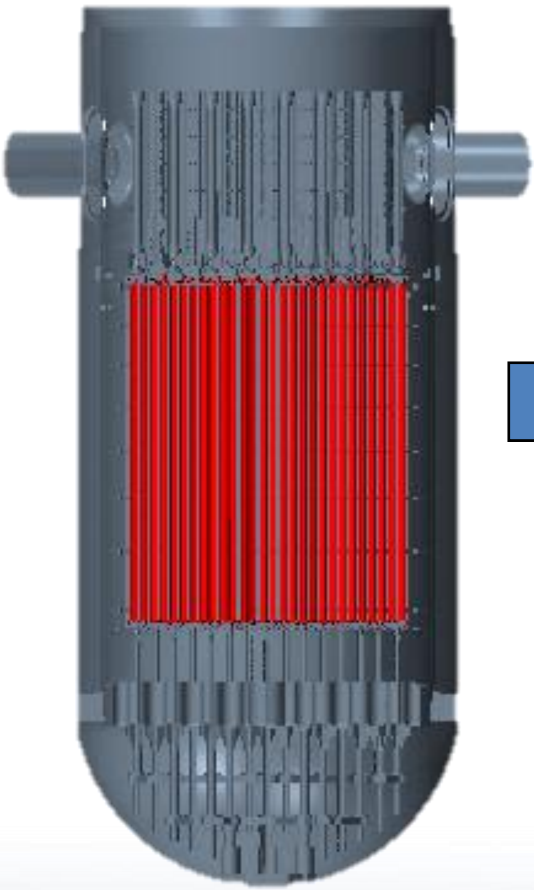
CAD Model



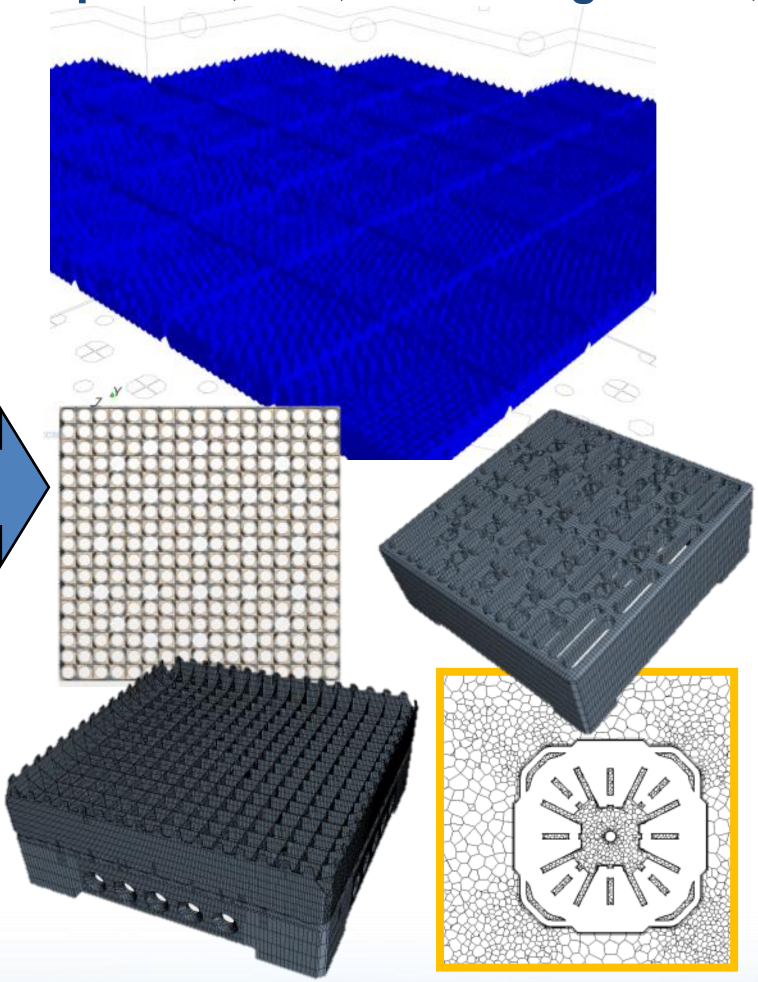
CFD Model

4-Loop Westinghouse PWR Multi-Physics Model Development

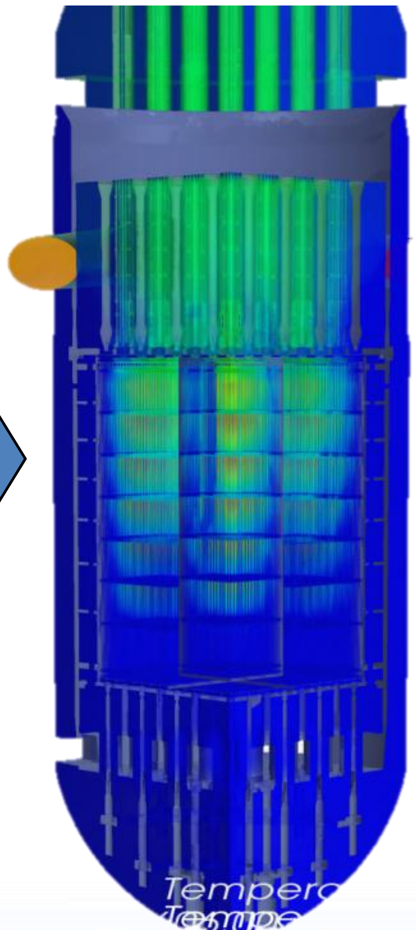
- RPV ID 173”, 193/4 Fuel Assemblies,13,944 fuel rods (fuel pellets, helium gap), 434 spacers, 148,224 mixing vanes; 1.2 billion cells



CFD Model



Mesh



Results