TAKING A FRESH LOOK AT BOILING HEAT TRANSFER ON THE ROAD TO IMPROVED NUCLEAR ECONOMICS AND EFFICIENCY

EMILIO BAGLIETTO

CASL Focus Area Lead for Thermal Hydraulics Methods and the Norman C. Rasmussen Associate Professor of Nuclear Science and Engineering at the Massachusetts Institute of Technology. He is a PhD Graduate in Nuclear Engineering from the Tokyo Institute of Technology.

W. DAVID POINTER

CASL Deputy Lead for Thermal Hydraulics Methods and a Distinguished Nuclear Engineer at Oak Ridge National Laboratory. He earned a PhD in Nuclear Engineering from the University of Tennessee.

In the effort to reinvigorate innovation in the way we design, build, and operate the nuclear power generating stations of today and tomorrow, nothing can be taken for granted. Not even the seemingly familiar physics of boiling water. The Consortium for the Advanced Simulation of Light Water Reactors, or CASL, is focused on the deployment of advanced modeling and simulation capabilities to enable the nuclear industry to reduce uncertainties in the prediction of multi-physics phenomena and continue to improve the performance of today's light water reactors and their fuel. An important part of the CASL mission is the development of a next generation thermal hydraulics simulation capability, integrating the history of engineering models based on experimental experience with the computing technology of the future.

UN NUEVO PUNTO DE VISTA A LA TRANSFERENCIA DE CALOR EN LA EBULLICIÓN PARA LOGRAR LA MEJORA EN LA EFICACIA Y EN LA ECONOMÍA NUCLEAR

En el esfuerzo de revitalizar la innovación en la manera en la que diseñamos, construimos y operamos las centrales nucleares del presente y del futuro, nada se puede dar por supuesto. Ni siquiera la supuestamente conocida física del agua en ebullición. El Consorcio para la Simulación Avanzada de Reactores de Agua Ligera (CASL) está centrado en el desarrollo de capacidades avanzadas de modelización y simulación para posibilitar a la industria nuclear reducir incertidumbres en la predicción de los fenómenos multifísicos y continuar mejorando el desempeño de los actuales reactores de agua ligera y su combustible. Una parte importante de la misión de CASL es el desarrollo de una nueva generación de capacidades de simulación termohidráulica, integrando los históricos modelos de ingeniería, basados en experimentos, con la tecnología computacional del futuro

CASL BRINGS NEW TOOLS AND SOLUTIONS TO NUCLEAR POWER

The Consortium for the Advanced Simulation of Light Water Reactors, or CASL, establishes innovative new modeling and simulation capabilities to improve the performance of today's light water reactors (LWRs). We work to enable safer and more cost efficient commercial nuclear power production through the application of predictive modeling and simulation technology which leverages recent advances in high performance computing technologies and solution methods. Towards that end, CASL's contributors from government research laboratories, universities, and industry partners, as shown in Figure 2, are developing VERA, the Virtual Environment for Reactor Application. VERA integrates representations of neutron transport, thermal-hydraulics, fuel performance, and coolant chemistry in order to predict complex multi-physics behaviors that may be observed in a particular fuel and reactor core design. See Ref. 1 for additional information.

Figure 1. CASL works to improve performance of today's light water reactors. Shown is the Watts Bar Nuclear Power Plant operated by the Tennessee Valley Authority.

Figure 2 The CASL team is led by Oak Ridge National Laboratory with major contributions from nine partner institutions.

In order to rapidly develop and deploy new modeling and simulation capabilities, the U.S. Department of Energy (DOE) established CASL as its first DOE Energy Innovation Hub in July 2010. DOE Energy Innovation Hubs engage multidisciplinary teams focused on different aspects of a single topic and rapidly integrate their capabilities to overcome the so-called "Valleys of Death" between basic research, engineering development, and commercialization.

Modeling and simulation is not new to the nuclear industry. In fact, modeling and simulation has been a critical tool that informs both operational planning and safety decisions since the very beginnings of the nuclear industry. Nuclear technology evolves slowly, relying on accumulation of experience and knowledge gained from decades of operation to inform engineering models which very accurately describe that accumulated experience. Even advanced light water reactors currently under construction around globe rely on the experience-based modeling and simulation technology. Our limited ability to perform full-scale, prototypic, in-reactor experiments due to cost, safety, technical feasibility, and economic uncertainty, keep us in this slow evolutionary progression. Meanwhile opportunities to realize improvements in economic and operational performance, through reduced uncertainty in design and operating margins, are lost.

Today, CASL has demonstrated the ability to leverage the power of the leading U.S. supercomputing facilities to establish sophisticated computational models which can be used to investigate potential operations in reactor cores containing hundreds of fuel assemblies, thousands of individual fuel rods, and millions of fuel pellets.

A NEW APPROACH TO THERMAL HYDRAULICS MODELING AND SIMULATION

Thermal hydraulics is one of the pillars of mechanical engineering education. Nearly every engineering student learns to dutifully look up thermal properties in steam tables and extract friction multipliers from Moody diagrams. Thermal hydraulics courses often introduce young engineers to one of the most important lessons in engineering training: engineering models only need to be accurate enough to meet the requirements of the analysis. As a consequence, thermal hydraulics design is often considered to be handbook engineering where descriptive, rather than predictive, empirical models must be produced. Empirical based model parameters must be constantly updated based on correlation to experiment, as required for major design changes. The Departure from Nucleate Boiling (DNB) correlation for a new fuel product is an example, where hundreds of measurements are required at significant expense. The high costs contribute to the slow evolution of nuclear fuel and reactor designs.

Substituting experience-based models for a more fundamental understanding of underlying phenomena is certainly of great value to support the continued application of current technology, but still limits our ability to adopt innovative advances in nuclear fuel and reactor designs to improve performance.

CASL is focused on the development of the next generation approach to thermal hydraulics modeling as part of its virtual reactor simulation capability. CASL's Thermal Hydraulic Methods (THM) team is working to develop and demonstrate new models which more accurately predict the behaviors of boiling flows in LWR cores. Our initial target application is the prediction of DNB, which is a condition in which the surface temperature of the fuel rod escalates rapidly as a consequence of a sudden change in the mechanism by which water on the surface of the rod is converted to steam. The margin to DNB is one of the most important operational margins; reduced uncertainty in prediction of DNB could enable today's nuclear power plants to produce even more power from each fuel assembly.

BRIDGING FROM EMPIRICAL MODELING TO PREDICTIVE SIMULATION WITH COMPUTATIONAL FLUID DYNAMICS

Computational Fluid Dynamics, or CFD, is the name applied to the broad class of numerical methods and codes that solve a discretized form of the well-known Navier-Stokes equations in order to predict the behavior of fluids as they pass through or over solid objects. CFD methods have been in use for single phase gas or liquid flows for many decades, and modern commercial computing platforms have enabled CFD analysis to become an integral part of the design process of many industries. However, the prediction of multi-phase boiling flow behaviors has remained elusive because multiphase boiling simulations have been viewed as too computationally expensive to be practically applicable. And the critically important closure models which

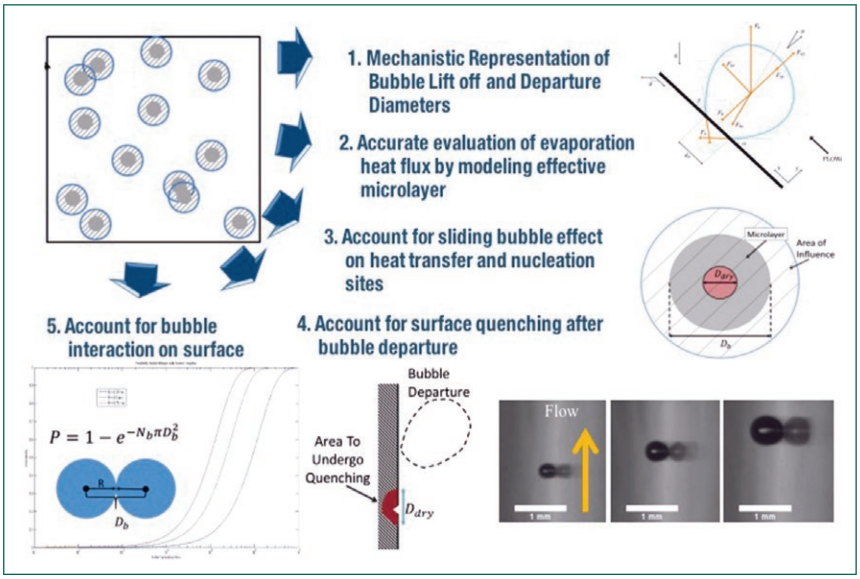

Figure 3. Summary of features of the novel subgrid scale wall-boiling representation employed by CASL THM.

model the behavior of various coefficients in the equation set remain underdeveloped. Recent advances in computational hardware and computing capacities have helped to address the first challenge and paved the way for more active development of new robust closure models as part of the CASL program.

The CASL THM team initially completed a comprehensive review of the current state of the art in multiphase boiling simulations using a mix of commercial, university and national laboratory codes (see Ref. 2). This broad study demonstrated the potential of Eulerian-Eulerian formulations to provide predictive simulations of boiling flow behaviors and also demonstrated the portability of robust new closure models between codes using this type of solution scheme. As a result of the study, CASL development efforts have focused in two areas: improved wall heat partitioning models to provide closure to the energy equations and improved bubble hydrodynamic models to provide improved momentum closures.

Our aim in developing the advanced wall heat partitioning model is to introduce all necessary mechanisms to accurately predict, using multi-phase CFD, the temperatures and heat fluxes associated with a fuel rod when sub-cooled boiling is occurring on the heat transfer surface. In multiphase CFD simulations, much of the important physics occurs at scales smaller than the computational mesh used to describe the geometry, and closure models are needed which accurately describe the boiling surface conditions within each computational mesh volume. Figure 3 highlights important features of the new modelling strategy. As illustrated in Figure 4, we can think of this model as effectively describing heat transfer from the surface as the combination of four effects: forced convection, evaporation, quenching as bubbles depart from the surface, and sliding conduction as bubbles move along the interface. Additional details can be found in Ref. 3.

An initial model has been implemented in the commercial finite volume CFD code STAR-CCM+ by the Massachusetts Institute of Technology (MIT) team led by Prof. Baglietto. An initial validation was performed, without model calibration, against data collected in the MIT flow boiling facility (see Ref. 4). Predicted boiling curves are shown in Figure 5 for simulations at 3 different pressures (1.05, 1.5 and 2.0 bar), 2 different inlet subcoolings (10°K or 15°K), and 3 different mass fluxes (500, 1000, and 1250 kg/m^2-s). Predicted wall temperatures agree well with the measured data and generally fall within the experimental uncertainty. More importantly the advanced model clearly provides an improvement in prediction of the boiling curve shape in comparison to the conventional model.

The multiphase CFD approach adopted by CASL relies on a local closure strategy in which local flow conditions are evaluated cell by cell to insure that the correct closure models are applied locally within that cell. The ensemble of the computational cells, which may each contain bubbly flow, droplet flow or something

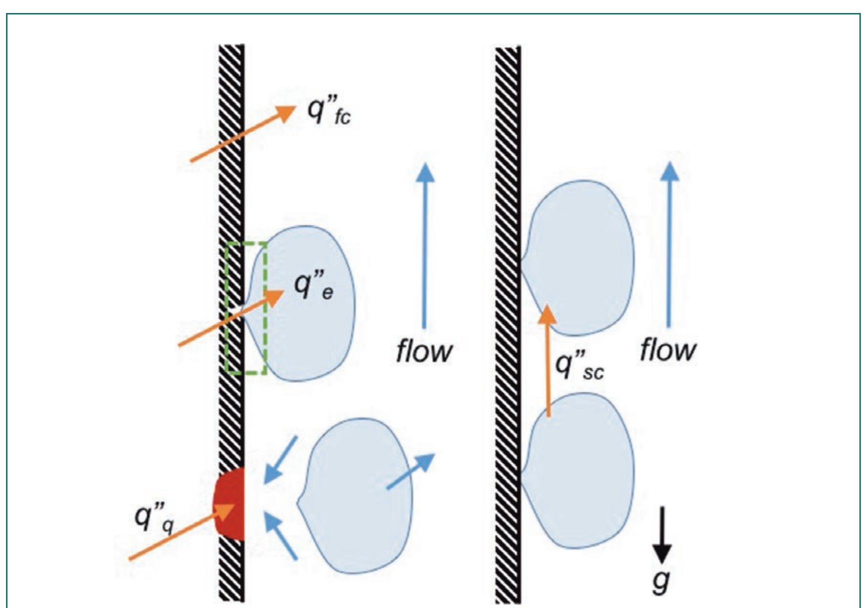

Figure 4. Illustration of the heat flux partitioning for subcooled flow boiling into forced convection (fc), evaporation (e), quenching (q) and sliding convection (sc) components.

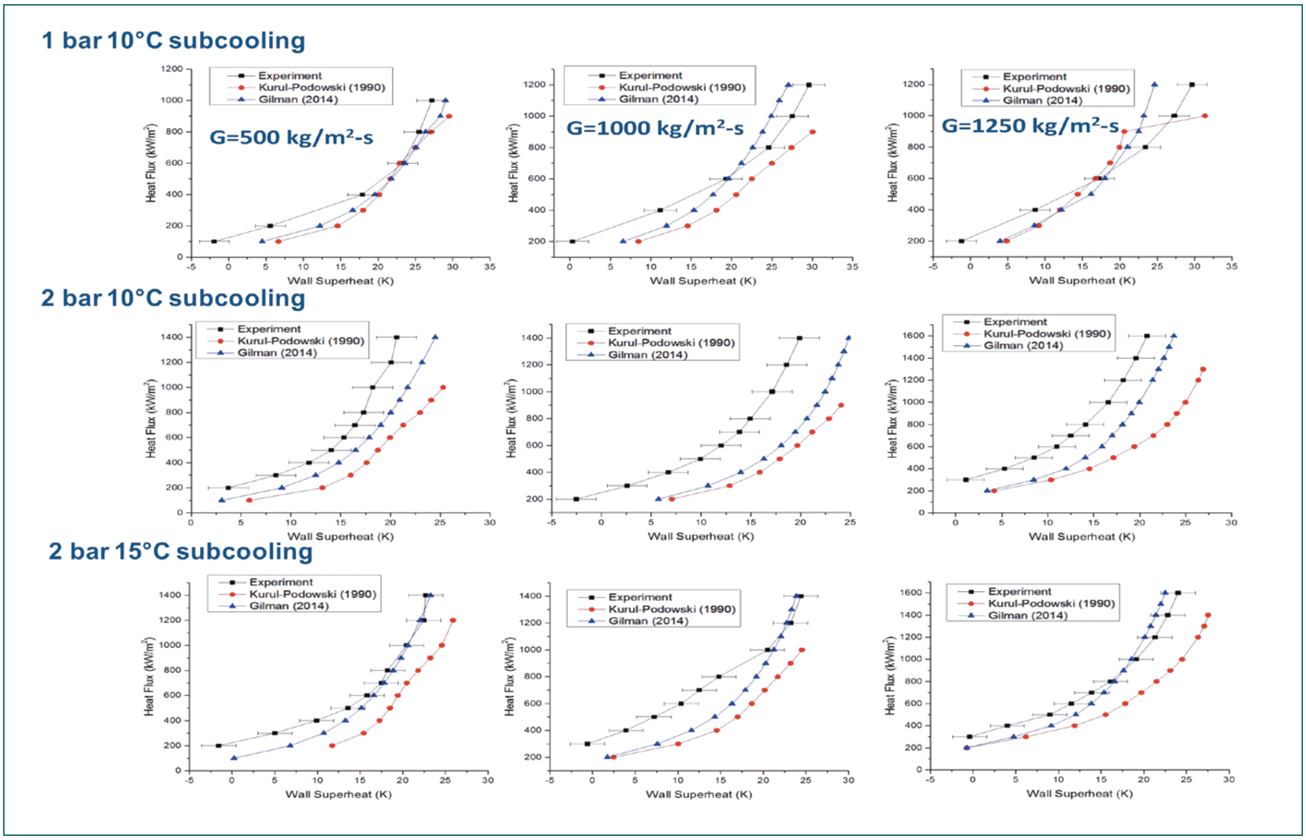

Figure 5. Average heater temperature predictions for the experiment, Kurul-Podowski model, and the recent model of Gilman for mass fluxes of 500,1000,1250 kg/m^2-s, pressures of 1.05 bar and inlet subcooling of 10 K, and 2.0 bar and inlet subcooling of 10 and 15K.

in between, may then combine to recreate the familiar map of flow regimes, as illustrated in Figure 6. The closure of the momentum equations requires the development of models which describe the subgrid forces acting on the secondary phase that strongly affect its distribution within the primary phase. Vapor bubbles passing through or carried by liquids are obviously subjected to hydrodynamic forces like lift and drag. However, additional terms may be required to differentiate between the behaviors of large vs small bubbles or bubbles near the wall vs in the bulk flow. Until very recently, the development of such closure models for multiphase CFD applications has relied on sparse experimental data from high-resolution multiphase flow experiments and more commonly available data from more sparsely instrumented experiments. CASL is augmenting this data with extremely high-resolution simulations of the behaviors of small populations of bubbles using high-fidelity Interface Tracking Methods (ITM) and Direct Numerical Simulations (DNS).

CASL's team of ITM/DNS researchers, led by Prof. Gretar Trygvasson of the University of Notre Dame and Prof. Igor Bolotnov of North Carolina State University (NCSU), are defining the the state of the art in multiphase CFD simulations with high-resolution ITM/DNS simulations of substantial bubble populations at relevant thermal hydraulic conditions. The ITM/DNS codes, which directly simulate the multiphase Navier-Stokes equations with very limited engineering approximation, provide the most exact solution of the highly non-linear system of equations that can be achieved. ITM/DNS simulations of reactor flow conditions, such as those

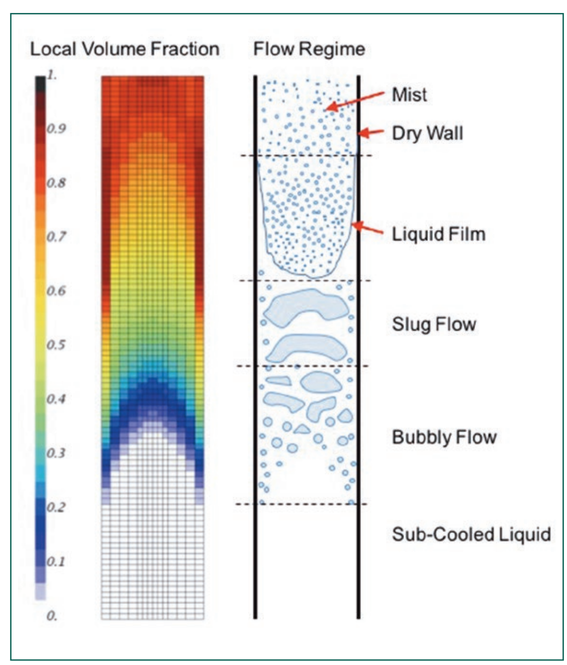

Figure 6. Multiphase CFD representation of boiling in a channel with local resolution of flow topology versus the conventional idealized flow region map.

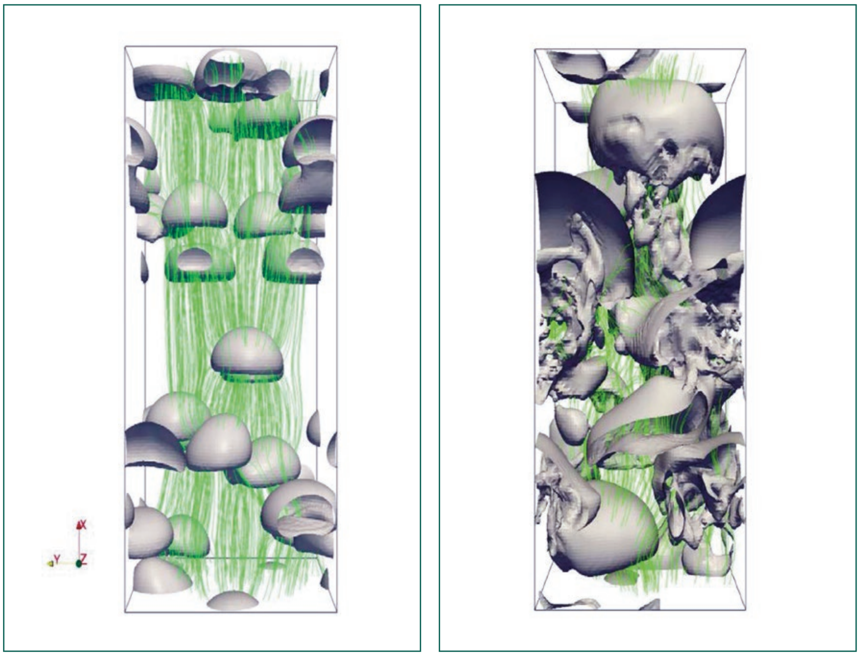

Figure 7. ITM/DNS Simulations of bubbly flow (left) versus churn-slug flow (right) conditions.

shown in Figure 7, were far beyond the reach of even the world's largest super computers until the current class of leadership computing facilities became available. In CASL, ITM/DNS tools are used to parametrically evaluate the sensitivity of bubble behaviors to a wide range of physical properties and parameters, including flow conditions, thermal conditions, thermophysical properties, and even coolant purity (see Ref. 3 and Ref. 5). These parametric assessments augment experimental measurements to support the development of more robust momentum closure models with a much broader range of applicability.

IS THIS THE END OF THE AGE OF EXPERIMENTS?

With access to high-resolution science-based simulation tools and large-scale computing systems that can be applied to parametrically assess the sensitivity of models applied in coarser representations, one might be tempted to wonder if we have escaped the need for experimental observations. Can we rely exclusively on increasingly refined simulation to establish the credibility of our models? The answer is, of course, a resounding no. While we can use these simulations to reduce our uncertainty in a model's predictions and make improvements to closure models, we can never escape the need for experimental observations and measurements to confirm that our fundamental system of equations really represents the real world or inspire us to establish new models which provide a more accurate representation.

CASL leverages measurements from a wide range of experimental facilities to support model development and validation. A team led by Prof. Jacopo Buongiorno at MIT makes fundamental measurements of bubble growth and departure at carefully engineered nucleation sites on both clean surfaces and surfaces covered in material which simulates the crud deposits that may grow on fuel rods during operation. These experiments both inspire and confirm the adopted approach to modeling of thermal transport. A second team led by Prof. Yassin Hassan of Texas A&M University (TAMU) makes high-resolution measurements velocity and temperature fields in two phase boiling flows in reactor fuel assembly geometries. These measurements of inform the development of new turbulence models for two phase boiling systems and aid in validating integrated multi-phase CFD simulations that combine all of the new closure models within a single CFD code.

Without such experimental efforts, development and validation of new mechanistic models would simply not be possible. However, separate effects data alone is not sufficient to demonstrate the accuracy of the predictive capabilities for real world problems. For final confirmations, CASL turns to its partners who provide access to experimental data from their own test facilities and even in-core measurements. CASL is revitalizing, advancing, and enhancing our experience-based approach to thermal hydraulics not replacing it.

ACKNOWLEDGEMENTS

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