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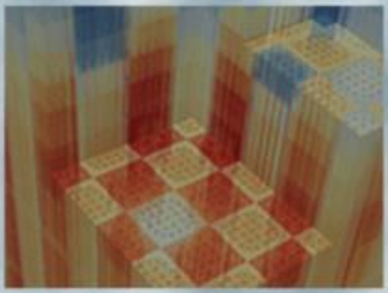
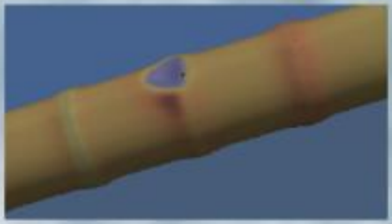
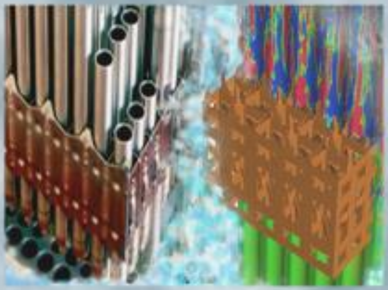




STAR-CCM+ Verification and Validation Plan



W. David Pointer
Oak Ridge National Laboratory

September 30, 2016

U.S. DEPARTMENT OF ENERGY | Nuclear Energy

REVISION LOG

Revision	Date	Affected Pages	Revision Description
0	09/30/2016	All	Initial Release

Document pages that are:

Export Controlled None

IP/Proprietary/NDA Controlled None

Sensitive Controlled None

Requested Distribution:

To: THM roster

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EXECUTIVE SUMMARY

The commercial Computational Fluid Dynamics (CFD) code STAR-CCM+ provides general purpose finite volume method solutions for fluid dynamics and energy transport. This document defines plans for verification and validation (V&V) of the base code and models implemented within the code by the Consortium for Advanced Simulation of Light Water Reactors (CASL). The software quality assurance activities described herein are part of the overall software life cycle defined in the CASL Software Quality Assurance (SQA) Plan [Sieger 2015].

STAR-CCM+ serves as the principal foundation for development of an advanced predictive multi-phase boiling simulation capability within CASL. The CASL Thermal Hydraulics Methods (THM) team develops advanced closure models required to describe the subgrid-resolution behavior of secondary fluids or fluid phases in multiphase boiling flows within the Eulerian-Eulerian framework of the code. These include wall heat partitioning models that describe the formation of vapor on the surface and the forces that define bubble/droplet dynamic motion. The CASL models are implemented as user coding or field functions within the general framework of the code.

This report defines procedures and requirements for V&V of the multi-phase CFD capability developed by the CASL THM team. Results of V&V evaluations will be documented in a separate STAR-CCM+ V&V assessment report. This report is expected to be a living document and will be updated as additional validation cases are identified and adopted as part of the CASL THM V&V suite.

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ACRONYMS

ALM	application lifecycle management
ANSI	American National Standards Institute
ASME	American Society of Mechanical Engineers
BFBT	boiling water reactor full-height bundle test
BWR	boiling water reactor
CASL	Consortium for Advanced Simulation of Light Water Reactors
CILC	crud induced local corrosion
CFD	computational fluid dynamics
DEBORA	experimental facility name (not an acronym)
DNB	departure from nucleate boiling
DOE	US Department of Energy
NRC	US Nuclear Regulatory Commission
NQA-1	Nuclear Quality Assurance Standard 1
PIRT	phenomena ranking and identification table
PSBT	pressurized water reactor subchannel and bundle test
PWR	pressurized water reactor
RANS	Reynolds Averaged Navier-Stokes
SLT	senior leadership team
STAR-CCM+	commercial CFD code name (not an acronym)
SQA	software quality assurance
SIMPLE	Semi-Implicit Method for Pressure-Linked Equations
THM	Thermal Hydraulics Methods (team)
V&V	verification and validation

1 INTRODUCTION

The commercial computational fluid dynamics (CFD) code STAR-CCM+, developed by CD-adapco, provides general purpose finite volume method solutions for fluid dynamics and energy transport. This document defines plans for verification and validation (V&V) of the base code and models implemented within the code by the Consortium for Advanced Simulation of Light Water Reactors (CASL). The software quality assurance (SQA) activities described herein are part of the overall software life cycle defined in the SQA Plan [Sieger, 2015].

This report defines procedures and requirements for V&V of the multi-phase CFD capability developed by the CASL Thermal Hydraulics Methods (THM) team. Results of V&V evaluations will be documented in a separate STAR-CCM+ V&V assessment report. This report is expected to be a living document and will be updated as additional validation cases are identified and adopted as part of the CASL THM V&V suite.

1.1 Code Methodology and Features

The commercial CFD code STAR-CCM+, developed by CD-adapco and used under license by CASL partners, serves as the principal foundation for development of an advanced predictive multi-phase boiling simulation capability within CASL. STAR-CCM+ provides a finite volume method fluid dynamics solution using the common Semi-Implicit Method for Pressure-Linked Equations (SIMPLE) with Rhie-Chow interpolation for pressure-velocity coupling and algebraic multi-grid preconditioning. The code provides a variety of Reynolds Averaged Navier-Stokes (RANS) turbulence modeling options and supports large eddy simulations. Second order accurate differencing schemes are generally applied in both space in time.

STAR-CCM+ offers several multiphase flow simulation options, including mixture modelling, volume of fluid methods, and a Eulerian-Eulerian dispersed phase capability. The CASL THM team develops advanced closure models required to describe the subgrid-resolution behavior of secondary fluids or fluid phases in multiphase boiling flows within the Eulerian-Eulerian framework of the code. These include wall heat partitioning models that describe the formation of vapor on the surface, and the forces that define bubble/droplet dynamic motion. CASL models are implemented as user coding or field functions within the general framework of the code.

1.2 STAR-CCM+ Use Cases

The advanced Eulerian-Eulerian multiphase boiling flow capability implemented in STAR-CCM+ is used in support of two CASL challenge problems: the prediction of crud induced localized corrosion (CILC) in pressurized water reactor (PWR) fuel assemblies and the prediction of departure from nucleate boiling (DNB) in PWR fuel assemblies. It is also the predictor of conditions in boiling water reactors (BWRs). Important phenomena for the prediction of CILC and DNB have been identified in phenomena ranking and identification tables (PIRTs) in the CASL V&V Plan [Mousseau and Dinh 2016]. These problems drive software development, as illustrated in Figure 2-1.

2 PROGRESSION PROBLEMS

A series of thermal hydraulics progression problems have been defined to help guide the development of the advanced boiling models and aid the THM team in assessing development progress. THM progression problems for single phase flow and heat transfer are defined in Table 2-1 and Table 2-2. Problem details have been defined by Smith, et al., in 2015. Similar cases are already included in the STAR-CCM+ test suite. These cases are included here for completeness but are unlikely to be tested explicitly in CASL. The two phase flow and heat transfer cases that are the primary focus of CASL THM are defined in

Table 2-3. Specific test cases are being developed as methodolgy is defined.

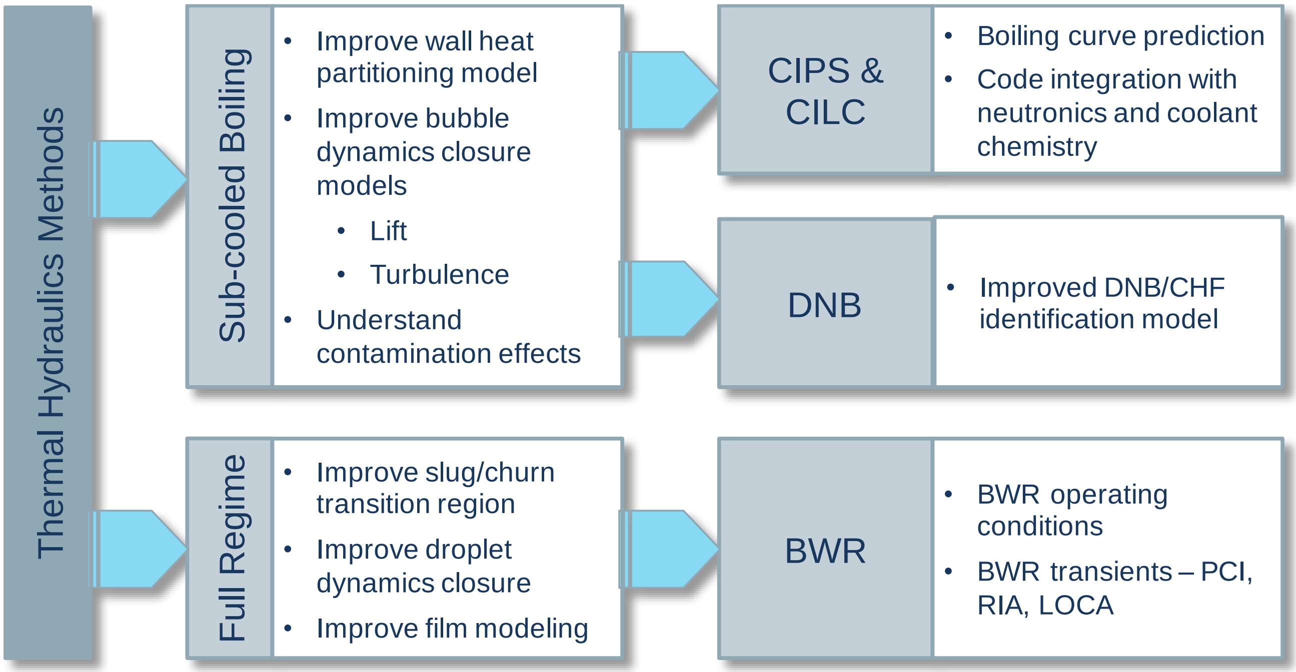


Figure 2-1. Notional view of development activity relationships to CASL challenge problems.

Table 2-1. Single phase isothermal progression problems.

Test	Objectives
Back step	Reattachment
Channel	Law-of-wall
Grid turbulence	Decay rate
Couette flow	Mean velocity profiles
Mixing layer	Scale similarity
Jets	Spreading rate
Pipe flow	Law-of-wall, Nu
J-channel	Curvature effects
Circular cylinder in crossflow	Strouhal No.
Asym. diffuser	Separation
Impinging jet	Stagnation point
Jet in crossflow	Complex vortex

Table 2-2. Single phase heat transfer progression problems.

Test	Objectives
Turbulent channel	Law-of-wall
Turbulent pipe flow	Temperature profile
J-channel	Curvature effects
Circular cylinder in crossflow	Crossflow heat transfer
Sub-channel	Secondary flow effects
Bundle/spacer segment	Secondary flow effects

Table 2-3. Two phase flow progression problems.

Test	Objectives
Vertical pipe	Lam. air/water bubbly flow
Vertical pipe	Turb. air/water bubbly flow
Vertical annulus	Lam. air/water bubbly flow
Vertical annulus	Turb. air/water bubbly flow
Vertical pipe	Laminar subcooled boiling
Vertical pipe	Turb. subcooled boiling
Vertical annulus	Laminar subcooled boiling
Vertical annulus	Turb. subcooled boiling
Sub-channel	Subcooled boiling secondary flow effects
Bundle/spacer segment	Subcooled boiling secondary flow effects
Vertical pipe	Lam. slug/churn two-phase
Vertical pipe	Turb. slug/churn two-phase
Vertical annulus	Lam. slug/churn two-phase
Vertical annulus	Turb. slug/churn two-phase
Sub-channel	Slug/churn secondary flow effects
Bundle/spacer segment	Slug/churn secondary flow effects
Vertical pipe	Lam. annular two-phase
Vertical pipe	Turb. annular two-phase
Vertical annulus	Lam. annular two-phase
Vertical annulus	Turb. annular two-phase
Sub-channel	Annular secondary flow effects
Bundle/spacer segment	Annular secondary flow effects

3 CODE QUALITY ASSURANCE

3.1 Quality Standards

STAR-CCM+ has historically been developed using an ISO9001 certified quality assurance process. More recently, CD-adpaco has begun to pursue commercial grade dedication for the code under the US Nuclear Regulatory Commission (NRC). A baseline is being developed which is compliant with the Nuclear Quality Assurance-1 (NQA-1) certification of the American Society of Mechanical Engineers (ASME). In of September 2016, a readiness review was successfully completed by CD-adapco, but the commercial grade dedication process continues. CASL is leveraging many improvements implemented as a consequence of the commercial grade dedication effort.

In addition to detailed user and methodology documentation, CD-adapco maintains a quality assurance manual which defines a continuous delivery strategy for the STAR-CCM+ code. The manual requires development of a project plan for each code change, including a clear test plan for code verification and definition of acceptance criteria. Among other data, project plans must identify:

- Related user/ methodology documentation
- Reference materials
- Test case descriptions
- Meshes and geometries
- Physical setup and boundary conditions
- Test data
- Limitations and risks
- Requirements
- Milestones
- Acceptance criteria

3.2 Change Management

3.2.1 STAR-CCM+

The STAR-CCM+ source code is maintained in a software repository which provides change tracking and version management. All development activities are planned, tracked, and assessed in the CD-adapco Application Lifecycle Management (ALM) system.

3.2.2 CASL THM User Coding and Field Functions

The models developed by the CASL THM team are implemented in STAR-CCM+ via user coding and field functions. The user coding functions are C or Fortran code which can be compiled with STAR-CCM+ and used to replace entire code features such as a lift force model in Eulerian-Eulerian models of multi-phase boiling flows. The field functions are java functions which can be used to define parameters in existing models or user coding.

Through the end of fiscal year 2016, user coding and field functions have been considered developmental, and version control has been left to individual users and developers. With the completion of a reasonably robust baseline in fiscal year 2016, more aggressive testing by the broader team will begin in fiscal year 2017. In preparation for this shift in prioritization, a more rigorous centralized change management system will be established in early 2017 based on the existing CASL repository and activity tracking systems.

3.3 Code Verification

Within CD-adapco, code verification cases are implemented with the STAR-TEST suite, which includes more than 30,000 individual test cases with baseline data stored in the internal data warehouse. The database includes both unit tests and application verification tests that may be based on standard validation problems. A fraction of all tests is automatically executed weekly, with results reported through the Application Lifecycle Management (ALM) system. All tests are executed before code releases.

A subset of the STAR-Test suite is distributed with the code as a customer verification suite. Although principally intended for confirmation of new local installations, the suite of 77 cases includes some cases relevant to the CASL THM development efforts and will serve as a baseline verification suite while more specific verification cases are being defined. The cases making up the customer verification suite are highlighted in

Table 3-1.

CASL specific verification cases will be defined as closure models are developed.

Table 3-1. Summary of cases included in STAR-CCM+ customer verification suite.

Aeroacoustics

- Noise emission from coaxial jets
- Propagation of a planar acoustic wave
- flow and energy
- Natural convection in an eccentric annulus
- Flow through an asymmetric plane diffuser
- Lid-driven flow in a two-dimensional square cavity
- Counter-flow heat exchanger in a two-dimensional channel modeled with periodic heat transfer
- Porous dominated flow
- “Darcy’s law” in one-dimensional incompressible flow using porous media
- Natural convection in a laminar square cavity with large temperature difference
- Karman vortex shedding
- Porous dominated swirling flow in an annulus
- Porous baffle
- Unsteady conduction heat transfer through a solid slab
- Non-Newtonian generalized Carreau-Yasuda flow in an axisymmetric pipe
- Natural convection between two infinite vertical walls
- Laminar high-capacity heat exchanger modeled with fully-developed energy
- Enthalpy source to mimic a heat exchanger
- Laminar flow of a viscoelastic fluid in cross flow
- Flow of viscoelastic fluid past a cylinder

Time

- Stokes’ first problem: the suddenly accelerated wall

Radiation

- Radiative heat transfer in scattering media using the discrete ordinate method
- Surface-to-surface radiation in an empty rectangular box
- Surface-to-surface radiation in a cylindrical hole
- Surface-to-surface radiation in a hollow cylinder
- Surface-to-surface radiation heat transfer reduction across a single shield
- Gray thermal radiation using a hexahedral mesh

Combustion

- Sandia piloted ch4/air jet flame d
- Turbulent lifted hydrogen flame
- Propane and air in a v-shaped combustor

LaGrangian multiphase

- Evaporation of multi-component droplets in dry air
- Turbulent dispersion of material particles in grid-generated turbulence

Eulerian multiphase

- Aeration tank with impermeable boundary for continuous water phase
- Polynomial specific heat for pressurized water
- Wall heat flux condition
- Bulk boiling
- Bozzano-Dente and Tomiyama drag laws
- Particle acceleration by drag
- Bulk boiling using s-gamma size distribution
- Rising terminal velocity of bubbles with drag laws
- Bubble acceleration under virtual mass force
- Tomiyama transverse lift coefficient with air bubbles
- Bubbly flow in water with variable density
- Fluid acceleration as a solid body
- Three phase particle terminal velocity
- Hydrotransport with turbulence
- Hibiki bubble column using s-gamma size distribution modeling
- Increase of bubble size due to pressure decrease in an ideal gas

Multiphase volume of fluid

- Free surface flow and heat transfer in a straight channel
- Flow in a capillary pipe
- Overset and non-overset: water impact of a wedge

Solid stress

- Stress analysis of a two-dimensional rectangular plate with a hole
- Fluid structure interaction using small displacement theory
- Deformation analysis of an elastic solid due to exerted fluid pressure

Finite element solid stress

- Finite-element bending of a cantilever beam
- Finite-element Scordelis lo roof

Electric potential

- Electric potential in a square domain

Compressible flow

- One-dimensional shock tube
- Supersonic flow over a flat plate
- Turbulent subsonic flow through an aero intake
- Turbulent transonic flow over an rae-2822 airfoil
- Quasi-1d converging-diverging nozzle flow
- Two-dimensional shock reflection

Turbulence

- Two-dimensional single-hill flows
- Turbulent compressible flow in a two-dimensional converging-diverging nozzle
- Fully developed turbulent pipe flow
- Turbulent natural convection in a heated cavity of aspect ratio 1
- Turbulent flow over a surface-mounted rib
- Turbulent flow in a channel using a wall-function mesh and a low-re mesh
- Two-dimensional transonic diffuser
- Turbulent flow and heat transfer over a backward-facing step
- Axisymmetric impinging turbulent jet with heat transfer
- T3a transition
- Turbulent flow in a swirling diffuser
- Curved turbulent channel flow
- Transitional boundary layer
- Turbulent natural convection in a heated cavity of aspect ratio 5

4 SOLUTION VERIFICATION

Unique solution verification standards have not been independently defined for the CASL team. The CASL THM team recommends the application of solution verification methods defined in the ASME Guide on Verification and Validation in Computational Fluid Dynamics and Heat Transfer, which was published as the American National Standards Institute (ANSI) V&V20 standard in 2009.

5 MODEL VALIDATION

A series of validation cases have been identified which track with the progression problems. The initial code and closure model validation matrix is summarized in Table 5-1. Key features of each case are summarized in the following sections. Validation assessments should generally follow the guidelines defined in the ASME Guide on Verification and Validation in Computational Fluid Dynamics and Heat Transfer, which was published as the American National Standards Institute (ANSI) V&V 20 standard in 2009. Limited application of the ANSI V&V 20 standard guidelines or the application of alternate guidance in lieu of the ANSI V&V 20 standard should be justified and documented in code V&V assessment reports.

Table 5-1. Summary of validation cases by geometry and flow regime.

	Bubbly flow	**Slug/churn flow**	**Annular flow**	**Departure from nucleate boiling**
Pin bundle geometry	BFBT	BFBT	BFBT	Westinghouse 5 × 5
Separate effects in simple geometry	Liu and Bankoff	Hibiki	Hibiki	Weatherhead
	Hibiki		Adamsson	
	Bartolomei			
	DEBORA			
	PSBT (subchannel)			

5.1 Liu & Bankoff (1993)

- Data source:
  - Liu, T. and Bankoff, S. (1993). Structure of air-water bubbly flow in a vertical pipe – 1. liquid mean velocity and turbulence measurements. *International Journal of Heat and Mass Transfer*, 36(4):1049–1060.
- Related CASL challenge problems
  - CRUD, DNB, BWR
- Coolant
  - Air injected into water flow
- Flow regime:
  - Bubbly
- Dimensions
  - Pipe diameter = 0.038 m
  - Channel length = 2.8 m
- Conditions
  - Adiabatic (283 K)
  - System pressure = atmospheric
  - Inlet superficial liquid velocity = 0.376 to 1.391 m/s
  - Inlet superficial gas velocity = 0.027 to 0.347 m/s
- Measurements
  - Local void fraction
  - Liquid velocity
  - Turbulent fluctuations

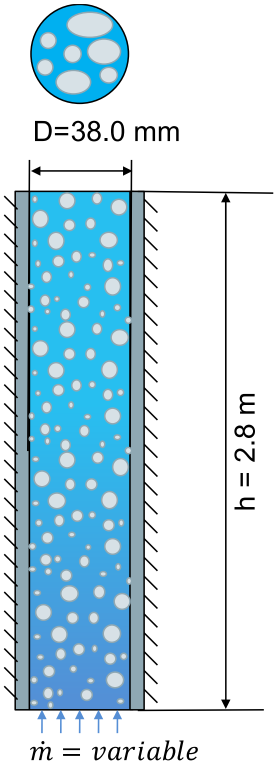


Figure 5-1. Channel characteristics for Liu & Bankoff validation cases.

5.2 Hibiki (1998 and 2001)

- Data sources:
  - Hibiki, Hogsett, and Ishii, “Local measurement of interfacial area, interfacial velocity and liquid turbulence in two-phase flow,” *Nuclear Engineering and Design* 184 (1998) 287–304.
  - Hibiki, Ishii and Xiao, “Axial interfacial area transport of vertical bubbly flows,” *International Journal of Heat and Mass Transfer* 44 (2001) 1869–1888.
- Related CASL challenge problems
  - CRUD, DNB, BWR
- Coolant
  - Air injected into water flow
- Flow Regime
  - Bubbly, slug churn, annular
- Dimensions
  - Pipe diameter = 0.0508m
  - Channel length = 3.658 m
- Conditions
  - Adiabatic (293 K)
  - System pressure = atmospheric
  - Inlet superficial liquid velocity = 0.491 to 5.0 m/s
  - Inlet superficial gas velocity = 0.0147 to 3.9 m/s
  - Inlet void fraction = 0.0130 to 0.442
- Data
  - LOCAL void fraction
  - INTERFACIAL area concentration
  - INTERFACIAL velocity,
  - Sauter mean diameter
  - LIQUID velocity
  - TURBULENT intensity

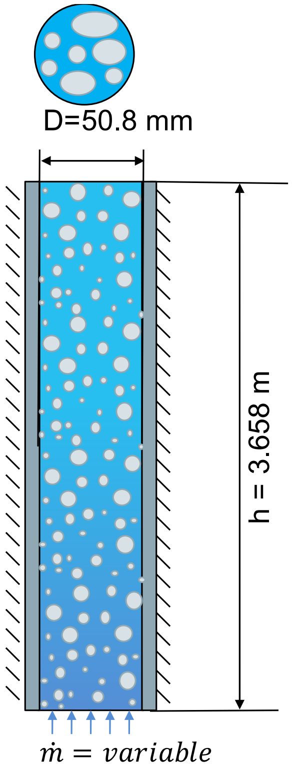


Figure 5-2. Channel characteristics for Hibiki validation cases.

5.3 Bartolomei & Chanturitya (1967)

- Data source:
  - G. G. Bartolomei and V. M. Chanturiya, “Experimental study of true void fraction when boiling subcooled water in vertical tubes,” *Thermal Engineering* **14**, 1967, 123–128, translated from Teploenergetika **14**, 1967, 80–83.
- Related CASL challenge problems
  - CRUD, DNB, BWR
- Coolant
  - Boiling water
- Flow Regime
  - Bubbly
- Dimensions
  - Pipe diameter = 0.0154m
  - Channel length = 2m
- Conditions
  - Wall heat flux = 0.57 MW/m^2
  - System pressure = 4.5 MPa
  - Inlet mass flux = 900 kg/m^{2}s
  - Inlet subcooling = 60 K
- Data
  - Void profile
  - Wall temperature profile
  - Bulk temperature profile

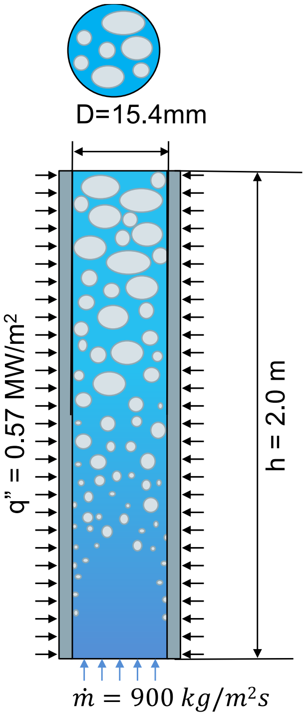


Figure 5-3. Channel characteristics for Bartolomei & Chanturitya validation cases.

5.4 DEBORA (from Yao and Morel, 2004)

- Data source:
  - Reported in Yao and Morel, “Volumetric interfacial area prediction in upward bubbly two-phase flow,” *International Journal of Heat and Mass Transfer* 47 (2004) 307–328.
- Related CASL challenge problems
  - CRUD, DNB, BWR
- Coolant
  - Boiling R12 refrigerant
- Flow Regime
  - Bubbly
- Dimensions
  - Pipe diameter = 0.0192 m
  - Channel length = 5 m (3.5 m heated)
- Conditions
  - Wall heat flux = 73.89 to 109.42 kW/m^2
  - System pressure = 1.459 to 2.617 MPa
  - Inlet mass flux = 1986 to 2981 kg/m^{2}s
  - Inlet subcooling = 16.1 ºK to 23.2 ºK
- Data
  - Local void fraction
  - Interfacial area concentration
  - Interfacial velocity
  - Sauter mean diameter
  - Liquid velocity
  - Turbulent intensity

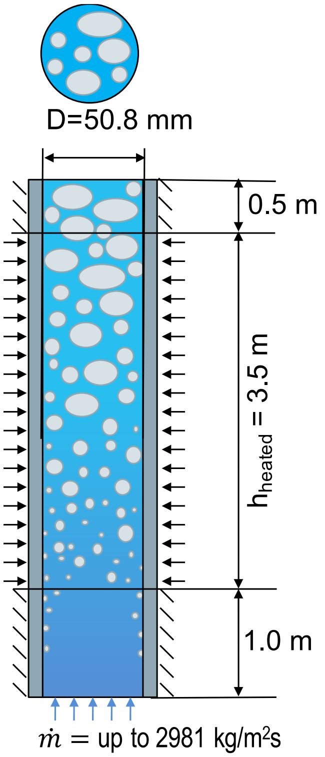


Figure 5-4. Channel characteristics for DEBORA validation cases.

5.5 PSBT Benchmark, Subchannel Cases

- Data source:
    - Rubin, A., et al. "OECD/NRC Benchmark based on NUPEC PWR subchannel and bundle tests (PSBT), Volume I: Experimental Database and Final Problem Specifications." US NRC/OECD Nuclear Energy Agency Benchmark (2010).
- Related CASL challenge problems
    - CRUD, DNB, BWR
- Coolant
    - Boiling water
- Flow regime
    - Bubbly
- Dimensions
    - Considered 4 subchannel geometries
    - Channel Width = 0.0157 m
    - "Rod" Diameter = 0.0126 m
    - Heated Channel length = 1.555 m
- Conditions
    - Test section power = 15 to 80 kW
    - System pressure = 4.9 to 16.6 MPa
    - Inlet mass flux = 550 to 4150 kg/m2s
    - Inlet coolant temperature = 413 to 618 K
- Data
    - Chordal void fraction
    - CT void fraction

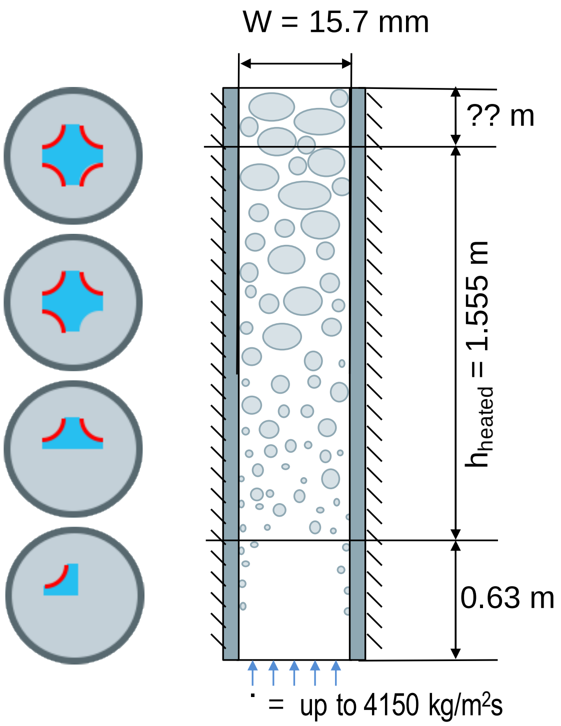


Figure 5-5. Channel characteristics for PSBT validation cases (four different subchannel cross sectional geometries considered are shown).

5.6 Weatherhead (1963)

- Data sources:
  - Weatherhead, R. J. "Nucleate Boiling Characteristics and The Critical Heat Flux Occurrence in Subcooled Axial-Flow Water Systems." ANL-6675, United States, (1963).
- Related CASL challenge problems
  - DNB
- Coolant
  - Boiling water
- Flow regime
  - Bubbly, DNB
- Dimensions
  - Pipe diameter = 0.0077 m
  - Channel length = 0.460 m
- Conditions
  - Wall heat flux = up to 6.0 MW/m^2
  - System pressure = 13.8 MPa
  - Inlet mass flux = 632 to 2712 kg/m^{2}s
  - Inlet subcooling = 10.46 kJ/kg to 1.313 MJ/kg
- Data
  - Void profile
  - Wall temperature profile
  - Bulk temperature profile
  - DNB

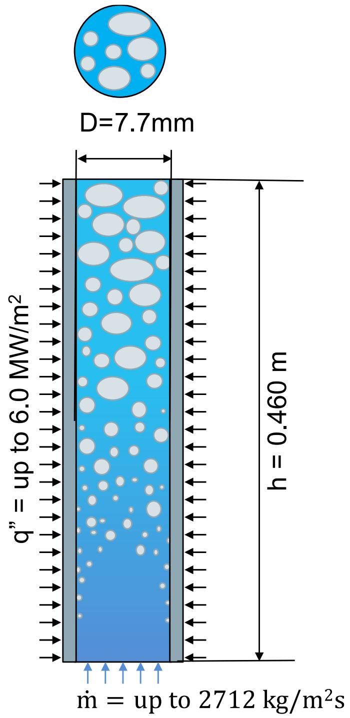


Figure 5-6. Channel characteristics for Weatherhead validation cases.

5.7 Adamsson and Anglart (2011)

- Data sources:
    - Adamsson, Carl, and Henryk Anglart. “A reinterpretation of measurements in developing annular two-phase flow.” *Nuclear Engineering and Design* 241.11 (2011): 4562–4567.
    - Adamsson, Carl. “Measurements of Film Flow Rate in Heated Tubes with Various Axial Power Distributions.” KTH Royal Institute of Technology (2006).
- Related CASL challenge problems
    - BWR
- Coolant
    - Boiling R12 refrigerant
- Flow regime
    - Annular
- Dimensions
    - Pipe diameter = 0.014 m
    - Channel length = 3.65 m
- Conditions
    - Wall heat flux = 0.74–1.0 MW/m^2
    - System pressure = 7.0 MPa
    - Inlet mass flux = 750–1450 kg/m2s
    - Inlet subcooling = 10 K
- Data
    - Film flow rate
    - Droplet flow rate
    - Void fraction distribution
    - Dryout

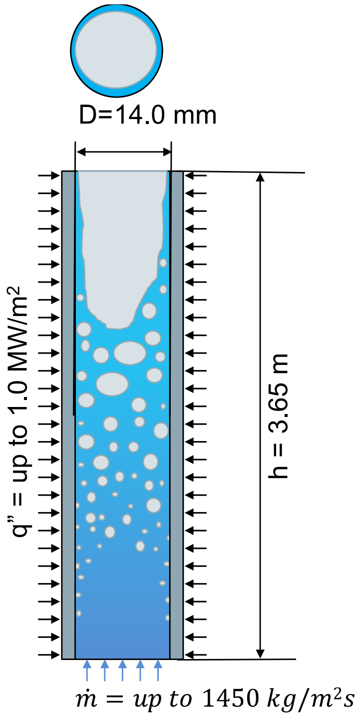


Figure 5-7. Channel characteristics for Adamsson and Anglart validation cases.

5.8 BFBT Benchmark

- Data source:
  - Neykov, D., et al. "NUPEC BWR Full-size Fine-mesh Bundle Test (BFBT) Benchmark: Volume I: Specifications." US NRC/OECD Nuclear Energy Agency Benchmark (2005).
- Related CASL challenge problems
  - BWR
- Coolant – boiling water
- Flow regime
  - Bubbly, slug churn, annular
- Dimensions
  - Channel box width = 0.1325 m
  - Rod configuration = 8 × 8
  - Rod diameter = 0.0123 m
  - Rod pitch = 0.0162 mm
  - Heated channel length = 3.7 m
- Conditions
  - Test section power = 15 to 80 kW
  - Axial power distribution = Uniform
  - Radial power distribution = Map
  - System pressure = 1.0 to 8.6 MPa
  - Inlet mass flow = 2.52 to 17.64 kg/s
  - Inlet subcooling= 20.9 to 126 kJ/K
  - Exit quality = 2% to 25%
- Data
  - Chordal void fraction
  - CT void fraction

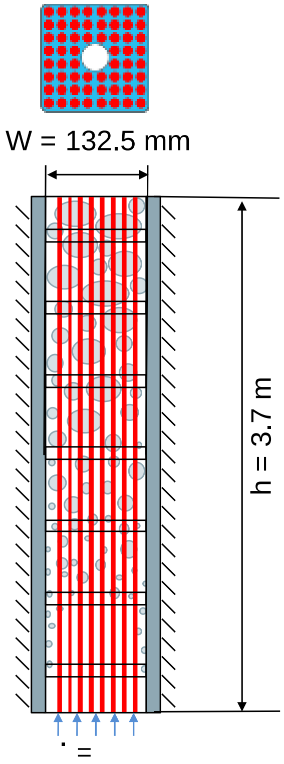
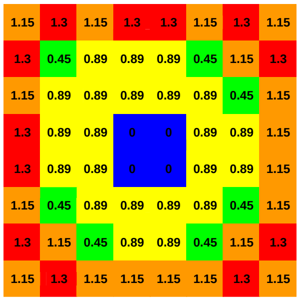


Figure 5-8. Channel characteristics for BFBT validation cases.



1.15	1.3	1.15	1.3	1.3	1.15	1.3	1.15
1.3	0.45	0.89	0.89	0.89	0.45	1.15	1.3
1.15	0.89	0.89	0.89	0.89	0.89	0.45	1.15
1.3	0.89	0.89	0	0	0.89	0.89	1.15
1.3	0.89	0.89	0	0	0.89	0.89	1.15
1.15	0.45	0.89	0.89	0.89	0.89	0.45	1.15
1.3	1.15	0.45	0.89	0.89	0.45	1.15	1.3
1.15	1.3	1.15	1.15	1.15	1.15	1.3	1.15

Q = up to 80 kW

Figure 5-9. Radial power profile for BFBT validation cases.

5.9 V&V Assessment Reporting

The results of each validation assessment will be documented in a code validation assessment report to be updated at least annually. Each validation assessment will be described in a separate chapter, which includes, at a minimum, the following information:

- Code version
- Verification of code installation
- Description of validation experiment
- Description of methodology, including detailed descriptions of user coding and/or field functions implemented by the user
- Assessment criteria
- Simulation results
- Solution verification
- Assessment results

6 ADDITIONAL CODES DEVELOPED OR USED BY CASL THM

The CASL THM team develops capabilities in or makes use of insights gained from four unique CFD platforms. STAR-CCM+, a commercial CFD code that serves as the principal framework for model development, is a 2nd order diffusion-limited, SIMPLE-based finite volume formulation with a Eulerian-Eulerian multiphase boiling flow model. OpenFOAM, and particularly the EulerFOAM module, is an open source CFD code that provides a 2nd order diffusion-limited, PIMPLE-based finite volume formulation with a Eulerian-Eulerian multiphase flow model. OpenFOAM is used to support development of advanced data integration strategies which would be difficult to implement within the framework of a commercial software package. FCT3D is a specialized pressure-projection predictor-corrector solver that supports front tracking for identification of gas-liquid interfaces in direct numerical simulations of bubbly flows. PHASTA is a high order finite element solver with a multiphase level set method for identification of gas-liquid interfaces in direct numerical simulations of bubbly flows. FCT3D and PHASTA are used to enhance understanding of underlying physics and establish databases for demonstration of multi-scale data integration.

This plan only addresses V&V of the advanced two-phase boiling capability developed within the framework of the STAR-CCM+ code. The other codes provide insight into underlying physics to support model development but are not expected to contribute directly to the solution of CASL challenge problems or the validation of the capabilities implemented in STAR-CCM+. As long as they do not contribute directly, V&V practices are left to their individual developers. However, consistency with the requirements defined for STAR-CCM+ herein is desirable and recommended.

7 ACKNOWLEDGEMENTS

The author gratefully acknowledges the support of CD-adapco staff, especially Gary Gauvin, Director of Application Lifecycle Management, and Eric Volpenhein, Senior Account Manager, in the development of this V&V plan. The author also gratefully acknowledges the support of the authors of the CASL V&V plan, Dr. Vince Mousseau of Sandia National Laboratory and Prof. Nam Dinh of North Carolina State University, for their insightful comments and discussions as the V&V plan was developed.

8 CONCLUSION

This document defines V&V plans for CASL multiphase boiling CFD models implemented within the commercial CFD code STAR-CCM+, developed by CD-adapco. This document defines or identifies documents which define expected practices for code version control, change management, code verification, solution verification, and model validation. This is a living documented that will be updated as additional verification tests and validation cases are adopted by the CASL THM development team.

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