ZACHRY

Boron Transport, Mixing, and Distribution Analysis Division

Introduction

GOTHIC™ is a versatile and generally applicable software package that solves complex thermal hydraulics problems. GOTHIC solves the conservation equations for mass, momentum and energy for multicomponent, multi-phase flow in lumped parameter and/or multi-dimensional geometries. A distinctive feature of GOTHIC is the ability to track components in the liquid field. This tracking capability, the fundamental physics included in GOTHIC (e.g., viscous shear, molecular and turbulent diffusion) and the use of second-order accurate advection schemes allow GOTHIC to accurately model boron tracking and mixing.

GOTHIC™ incorporates technology developed for the electric power industry under the sponsorship of EPRI, the Electric Power Research Institute.

Boron Transport, Mixing and Distribution

Boron transport and mixing can be important for:

- Boron dilution transients and the potential for recriticality
- Establishing the hot leg injection switchover time follow a large cold leg break
- Determining the potential for boron precipitation associated with long-term cooling

Highly ranked phenomena for accurately capturing fluid mixing and localized boron concentration in the downcomer, lower plenum, and core regions include:

- Solute tracking capability
- Full treatment of the fluid-fluid stress terms in the momentum equations
- Diffusion (both molecular and turbulent)
- Second-order accurate advection schemes
- Natural circulation flow (both in-vessel and in the loops)
- Boil-off due to decay heat leading to an increased boron concentration within the vessel

GOTHIC includes all of these attributes and has recently been benchmarked against a series of boron mixing experiments.

Component Tracking

The component tracking capability included in GOTHIC is very flexible and allows for materials such as aqueous solutions (e.g., boric acid), solid particles (e.g., debris), or dissolved gases to be tracked. Each component is characterized by user defined values for the material density and specific heat. Boron can be treated as a component in the liquid phase with proper input for the material characteristics. If appropriate, values for characteristic diameter, a shape factor, and maximum allowable packing fraction can also be specified.

GOTHIC models the convective transport as well as molecular and turbulent diffusion for each tracked component. GOTHIC also includes models for settling and formation of a sediment layer, bed load (transport or spreading of settled material), resuspension of the settled material due to shear and turbulence, and release/absorption of dissolved gas. The fraction of each component that is suspended versus settled is tracked separately in each computational volume.

The momentum and energy equations for the continuous liquid field use effective fluid mixture density and heat capacity values that are calculated based on the volume occupied by the component. GOTHIC allows for relative motion in the vertical direction due to gravitational settling. A settling velocity, which can be positive or negative, is calculated individually for each component using a force balance that accounts for buoyancy effects. These capabilities make GOTHIC suitable for modeling conditions where stratification may occur.

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Fluid-Fluid Stress Terms and Diffusion Mechanisms

GOTHIC provides a 3-dimensional treatment for multiphase flow, including the full treatment of the fluid-fluid stress terms that govern momentum transport due to mixing. GOTHIC considers both viscous shear and turbulent diffusion of momentum, where a two-equation turbulence model is used to calculate the turbulent diffusion coefficients. GOTHIC also includes the effects of molecular, thermal, and turbulent diffusion in the fluid mass and energy equations. Additionally, both molecular and turbulent diffusion contributions are considered in the component (e.g., boron) mass balance equation. All of these terms and contributions are required to accurately capture the localized boron concentration.

2nd Order Accurate Advection Schemes

GOTHIC includes second-order accurate spatial schemes for the convection terms in the mass, energy and momentum balances. These schemes allow GOTHIC to more accurately model boron transport by reducing the amount of numerical diffusion relative to the first-order upwind schemes that are traditionally applied in thermal-hydraulic codes within the nuclear industry. This is important for capturing and preserving sharp concentration or temperature gradients.

Qualification

GOTHIC has been developed and maintained over 30+ years by the Analysis Division of Zachry Nuclear Engineering, Inc. It has been used for the design, licensing, safety and operating analysis of nuclear power plant systems including primary system, containment and equipment performance. GOTHIC includes the necessary modeling capabilities to represent the piping, reactor vessel, and components of the reactor coolant system. It has an extensive qualification basis and is developed under a QA program that is conforms to US-NRC 10CFR50 Appendix B.

Simulations have been performed to validate GOTHIC against boron transport and mixing experiments. International Standard Problem (ISP-) 43 represents transport and mixing of un-borated fluid in the vessel following the actuation of a pump (Reference [2]). These experiments were conducted at the University of Maryland in a 2x4 thermal hydraulic loop that is representative of a ~1/5 scale model of the Babcock and Wilcox (B&W) plant. Injection of cold water was used to represent un-borated fluid and the response due to downcomer mixing was captured using 265 thermocouples.

Figure 1 provides a snapshot of the mixing pattern circumferentially around the downcomer predicted by GOTHIC for one of the experiments. The 4 open circles represent locations of the 4 cold legs connected to the downcomer and 2 closed circles represent locations of 2 hot leg blockages. Cold water injection only occurs in one of the cold legs. GOTHIC is able to capture the distinct attributes of the transient, including the transition in flow pattern for momentum versus buoyancy driven mixing scenarios.

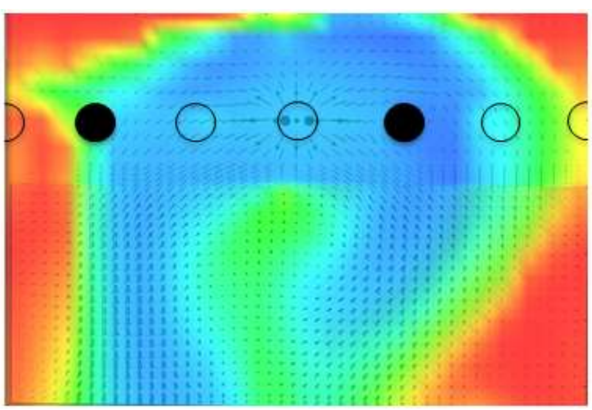

Figure 1. Snapshot of temperature contours and velocity vectors for GOTHIC Simulation of ISP-43.

Animations of these GOTHIC results are available for download from: http://www.numerical.com/gothic_boron.php.

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Figure 2 compares the GOTHIC predicted temperature response to the experimental data at two different elevations within the downcomer. These results validate that GOTHIC accurately captures both the magnitudes and trends of important figures of merit from the experiment.

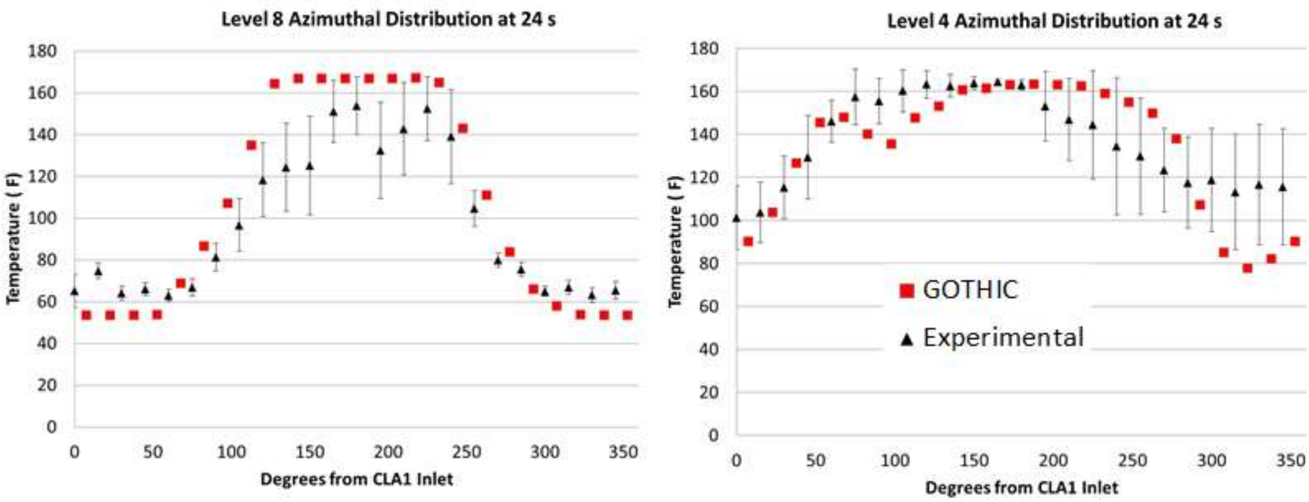

Figure 2. Code-to-data comparison of circumferential temperature distribution for ISP-43.

This benchmark has provided further proof that GOTHIC provides a computationally efficient solution without sacrificing accuracy. The GOTHIC simulations used significantly fewer computational cells and proved to be more accurate than several of results obtained using CFD that were presented in Reference [2]. These results, along with others documented in Reference [3], demonstrate that GOTHIC is capable of modeling the phenomena relevant to boron mixing. Additional benchmarks of mixing experiments using data from the ROCOM and Vattenfall facilities as well as other industry relevant tests are planned.

Recent Enhancements

Starting in GOTHIC 8.2 it is possible to track multiple components (both number and type) in the liquid and droplet fields. This particle tracking capability can be applied for such applications involving the transport, settling and resuspension of debris, aerosols and other materials with different characteristic sizes/properties. This capability, together with a generalized filter component that can remove specified fractions of the liquid components from the flow and maintain an inventory of the retained materials, can be used to support resolution of GSI-191 related issues. The ability to track dust and other dry aerosols can be used for dose, radiological or air quality assessments. Additional enhancements were made in GOTHIC 8.3 to improve computational efficiency and code robustness for these types of applications. Additional details are available in Reference [4] or by contacting Jeffrey Lane (lanejw@zachrynuclear.com, 919-903-6763) or Jim Harrell (harrelljr@zachrynuclear.com, 919-465-7230 x227).

References

1. *GOTHIC Thermal Hydraulic Analysis Package, Version 8.1(QA)*. EPRI, Palo Alto, CA: 2014.
2. NEA/CSNI/R(2000)22, ISP-43: Rapid Boron Dilution Transient Experiment, Comparison Report, OECD/CSNI Report.
3. P. Skelton and J. W. Lane, “Validating GOTHIC against Rapid Boron Dilution Transients (ISP-43)”, Paper #16503, International Congress on Advances in Nuclear Power Plants (ICAPP16), San Francisco, CA, April 2016.
4. J. W. Lane and T. L. George, “Development of a Multiple Liquid Component Capability in GOTHIC to Better Support Boric Acid, Radiological, and GSI-191 Analyses”, NURETH-16, Chicago, IL, August 2015.