COMPARISON OF COBRA-TF AND VIPRE-01 AGAINST LOW FLOW CODE ASSESSMENT PROBLEMS

A. Galimov[a], M. Bradbury[b], G. Gose[c], R. Salko[d], C. Delfino[a]

[a]NuScale Power LLC, 1100 Circle Blvd., Suite 200, Corvallis, OR 97330, USA,
cdelfino@nuscalepower.com

[b] Information Systems Laboratories, Inc.
11140 Rockville Pike, Suite 650, Rockville, MD 20852, USA

[c]Zachry Nuclear Engineering, Inc.,
410 Memorial Dr., Suite 205,Idaho Falls, ID 83402, USA

[d]Oak Ridge National Laboratory/CASL,
P.O. Box 2008, Oak Ridge, TN 3783, USA

ABSTRACT

NuScale Power LLC (NuScale) is developing a Small Modular Reactor that relies on natural circulation to provide primary flow. NuScale, therefore, requires a subchannel analysis code that is applicable to its unique operating conditions, such as low coolant flow, in the reactor core. The primary purpose of this study is to compare the existing subchannel codes VIPRE-01 and COBRA-TF (CTF) to examine their relative strengths and weaknesses. A secondary purpose is to identify areas for code improvement at NuScale plant operating conditions.

VIPRE-01 and CTF have a common lineage as both codes evolved from earlier COBRA code versions. VIPRE-01 is extensively used in the United States for safety analysis. CTF has the capability for two-fluid and void drift modeling.

A representative set of experimental test cases (including well-known test models like GE 3x3[1], and etc.) were selected to focus on phenomena of specific interest to the NuScale reactor. Parameters such as channel flows, temperatures, pressures, void fractions, and ability to converge at low flow and pressure conditions were compared for several different power, flow, and exit quality conditions.

Both the VIPRE-01 and CTF comparisons showed reasonable results for some cases while other cases indicated the need for additional investigation or model improvement. The comparative study has been useful in identifying the two codes relative strengths and weaknesses as well as providing direction for additional development. All benchmark activities have been conducted in cooperation with Zachry Nuclear Engineering, Inc. and Oak Ridge National Laboratory/CASL.

References

[1]. R. Lahey et al, "Two-Phase Flow and Heat Transfer in Multirod Geometries: Subchannel and Pressure Drop Measurements in a Nine-Rod Bundle For Diabatic and Adiabatic Conditions," GEAP-13049, General Electric Company, San Jose, CA, USA (1971).

KEYWORDS

Subchannel Analysis, COBRA-TF, VIPRE-01, Low Coolant Flow, NuScale

1 INTRODUCTION

NuScale Power LLC (NuScale) is developing a Small Modular Reactor that relies on natural circulation to provide primary flow. NuScale, therefore, requires a subchannel analysis code that is applicable to its unique operating conditions (i.e. low coolant flow) in the reactor core. The primary purpose of this study is to assess the existing subchannel codes VIPRE-01[1] and CTF[2,3,4] to examine their relative strengths and weaknesses at these types of conditions. A secondary purpose is to identify areas for code improvement at NuScale plant operating conditions.

VIPRE-01 and CTF have a common lineage, as both codes evolved from earlier COBRA code versions. VIPRE-01 is extensively used in the United States for safety analysis of operating plants. CTF has the capability for two-fluid and void drift modeling.

A representative set of experimental test cases were used to focus on phenomena of specific interest to the NuScale reactor. Two well-known test models (GE 3x3[5] and PNNL 2x6[6]) are the subject of assessment of this article. Parameters such as channel flows, temperatures, pressures, void fractions, and ability to converge at low flow and pressure conditions were compared for several different power, flow, and exit quality conditions.

This paper presents VIPRE-01 and CTF models used for assessment of the test cases along with discussion of code-to-code and code-to-data comparisons performed. The comparative study has been useful in identifying the two codes relative strengths and weaknesses as well as providing direction for additional development. All benchmark activities have been conducted in cooperation with Zachry Nuclear Engineering, Inc[7], and Oak Ridge National Laboratory/CASL[8].

2 OVERVIEW OF VIPRE-01 AND CTF CODES

2.1 VIPRE-01

VIPRE-01 (Versatile Internals and Component Program for Reactors) was originally developed by Battelle Pacific Northwest Laboratories for the Electric Power Research Institute. Presently, Zachry Nuclear Engineering, Inc. operates the VIPRE User Group and manages the latest code developments. VIPRE-01 solves the three-dimensional finite-difference equations for mass, energy, and momentum conservation for an interconnected array of channels, assuming incompressible thermally expandable homogeneous flow. The equations are solved with no time-step or channel size restrictions for stability. Although the formulation is homogeneous, empirical models are included for subcooled boiling and vapor/liquid slip in two-phase flow. VIPRE-01 is a safety related code that complies with the requirements of 10 CFR 50 Appendix B and is extensively used in the United States for safety analysis.

2.2 CTF

The original COBRA-TF software was developed by Pacific Northwest National Laboratory in 1980[3].Since then, various academic and industrial organizations have adapted and further developed the code, resulting in many variants of the original tool. The Reactor Dynamics and Fuel Management Group (RDFMG) at the Pennsylvania State University procured the code in the 1990s and rebranded it with the shorthand name, CTF, after further developing the software. This version of the code is now being jointly developed by Pennsylvania State University and Oak Ridge National Laboratory under sponsorship of the US Department of Energy Consortium for Advanced Simulation of Light Water Reactors (CASL). CTF is serving as the subchannel thermal hydraulic capability in the Virtual Environment for Reactor

Applications Core Simulator (VERA-CS) being developed in CASL[4]. This version of COBRA-TF has been used as part of the benchmarking study presented in this paper.

CTF is a transient code based on a separated flow representation of two-phase flow. It separates the conservation equations of mass, energy, and momentum to three fields: vapor, continuous liquid, and entrained liquid droplets, which results in a set of nine time-averaged conservation equations. It is capable of modeling both solid structures (e.g., unheated conductors and nuclear fuel rods) as well as the fluid regions of the core. It has models for simulating both normal operating conditions as well as accident conditions (loss-of-coolant accident) due to its inclusion of constitutive models for both normal (single phase, small and large bubbles) and hot-wall (inverted annular, dispersed droplet, and falling film) flow regimes. Additional models include void drift, turbulent mixing, and grid-spacer heat transfer enhancement. Recently, this version of CTF has undergone a significant amount of validation testing, resulting in creation of a validation manual for the code[4].

3 TEST DESCRIPTIONS

3.1 PNNL 2x6-Rod Bundle Buoyancy Flow Tests

The PNNL 2x6 Rod Bundle Flow test program[6] was performed in a 2-by-6 apparatus for both steady-state and transient situations. The purpose of the test campaign was to provide benchmark data to evaluate the ability of codes to account for the effects of buoyancy on flow patterns. The experimental rod bundle contained twelve electrically heated rods (see Figure 1 below). The rods were 0.475 inches in diameter with a 4-ft uniformly heated length and were spaced on a 0.575-in. pitch. The 12 rods were divided into two groups of six, each forming a 2 x 3 array which were connected to different, independently controlled power supplies. In this manner, radial power distributions of interest were established by setting the two power supplies at the desired value. The rod bundle was contained within a stainless steel flow housing having nine equally spaced windows located along its length. At these axial positions, detailed velocity profiles were measured with a one-dimensional laser Doppler anemometer (LDA) and fluid temperatures of the central subchannels were taken. This experiment was the first known attempt to apply the LDA velocity measurement technique to mixed free and forced convection in rod bundle flows.

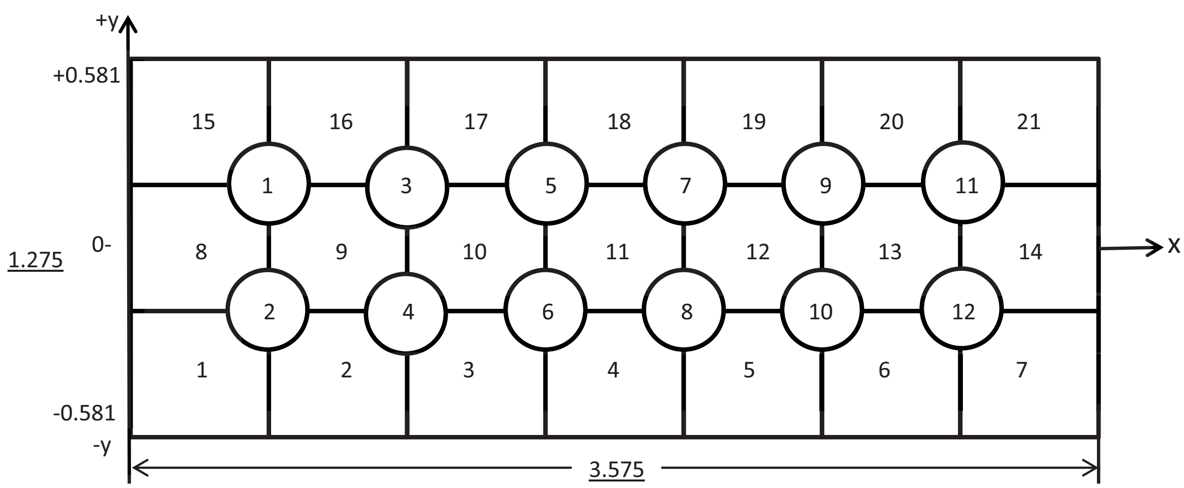

Figure 1.PNL 2x6 Rod bundle Flow test

Under these conditions, the fixed inlet flow was re-distributed across the bundle by temperature gradients due to differing powers on the two sides. Specifically, for both steady-state and transient problems, three rows of heater rods on one side were given power, while those on the other side were unheated.

The apparatus contained 9 windows at 6-inch intervals along its 4-ft heated length. At these elevations, a laser Doppler anemometer (LDA) was used to measure velocities along lines at 3 locations (Y = -0.581, 0.0, 0.581), which correspond to the three subchannel rows along the 2-rod dimension. Additionally, thermocouple measurements were made in several subchannel centers at these same elevations. For the scoping analysis the following test case was chosen:

- Steady State, Test Run 2. Quantities for evaluation by subchannel analysis: normalized subchannel velocity and temperature vs distance from wall for code prediction and measured data.

3.1.1 VIPRE-01 and CTF Modeling options

Table I and Table II provides a brief overview of the VIPRE-01 and CTF subchannel modeling options and boundary conditions used to simulate the test calculations.

Table I. Comparison of the VIPRE-01 and CTF subchannel models

Parameter	VIPRE-01	CTF
Friction Correlation	Max of 64/Re and 0.184 $Re^{-0.2}$	Max of 64/Re and 0.204 $Re^{-0.2}$
Solution Method	RECIRC	DIRECT (ISOL=0)
Heated Length	4’	4’
Void Drift Model	No	No

Table II. Boundary Conditions for PNNL 2x6 Calculations

Parameter	VIPRE-01	CTF
Pressure(psi)	60	60
Inlet Temperature [F]	60	60
Flow Rate [gpm]	1.25	1.25
Power per Rod [kW]	0.91	0.91

3.2 GE 3x3-Rod Bundle Two-Phase Flow Tests

This experiment (3x3 multi-rod BWR-type simulation) was one of the earliest investigations of the mixing phenomena in the rod bundle. In particular, this was one of the first investigations of the void drift phenomena by which void migrates from lower velocity subchannels to higher velocity subchannels.
The test was comprised of nine rods, all with an outer diameter of 14.5 mm (0.571 inches) and a pitch of 18.7 mm (0.736 inches). The bundle shroud has corners with a radius of 10.2 mm (0.402 inches) and its walls have an inner width of 58.83 mm (2.316 inches). The heated length is 1828.8 mm (72 inches). The system pressure is 68.948 bar (1000 psia). Figure 2 shows the geometry of the heated rods as well as the subchannel boundaries.

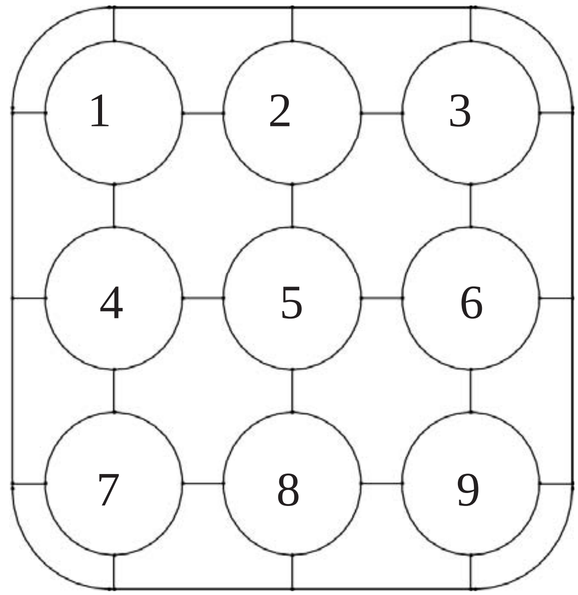

Figure 2.GE 3x3 Bundle Two-Phase Flow Test

Parameters selected for evaluation of the subchannel analysis were:

- Normalized subchannel mass flux vs bundle average quality for code predictions and measured data
- Normalized subchannel enthalpy flux vs bundle average quality for code predictions and measured data
- Calculated axial void fraction distribution for code to code comparison

3.2.1 VIPRE-01 and CTF Modeling Options

Table III and Table IV provides a brief overview of VIPRE-01 and CTF subchannel modeling options used to simulate the test calculations.

Table III Comparison of the VIPRE-01 and CTF subchannel models

Parameter	VIPRE-01	CTF
Number of Rods	9	9
Number of subchannels	16	16
Friction Correlation	Max of 64/Re and 0.184 $Re^{-0.2}$	Max of 64/Re and 0.184 $Re^{-0.2}$
Mixing Model	Single phase Turbulent mixing with β=0.06 applied for both phases	Rogers and Roseheart mixing model with β=0.02
Solution Method	RECIRC	Iterative Krylov
Void Drift Model	No	Yes
Pressure Losses	loss coefficients of 0.3360, 0.1629, and 0.1504 for the corner, side, and center subchannels, respectively	loss coefficients of 0.3360, 0.1629, and 0.1504 for the corner, side, and center subchannels, respectively
Subcooled/Bulk Void model	EPRI/EPRI	Thom/Thom

Table IV. Boundary Conditions for GE 3x3 Calculations

Test Series[4]	Power (kW)	Bundle-averaged flow rate (kg/s)	Subcooling (kJ/kg)
2B2	532	1.360	348.4
2B3	532	1.373	252.6
2B4	532	1.373	122.7
2D1	1064	1.386	602.4
2D3	1064	1.386	289.1

4 RESULTS AND DISCUSSION

VIPRE-01 and CTF results for the PNNL 2x6 tests are illustrated in Figure 3 and Figure 4. Both codes predict the effect of buoyancy on flow patterns and demonstrate similar trends in the case of single phase calculations, but VIPRE-01 has slightly higher velocity predictions compared to the CTF results. The temperature predictions of both codes demonstrate significant over-prediction on the heated side of the test bundles, which may be explained by the impact of the measurement uncertainty and temperature gradients within subchannels that could cause the subchannel average and subchannel center-point values to be different (see p. 7 of Ref. [6]).

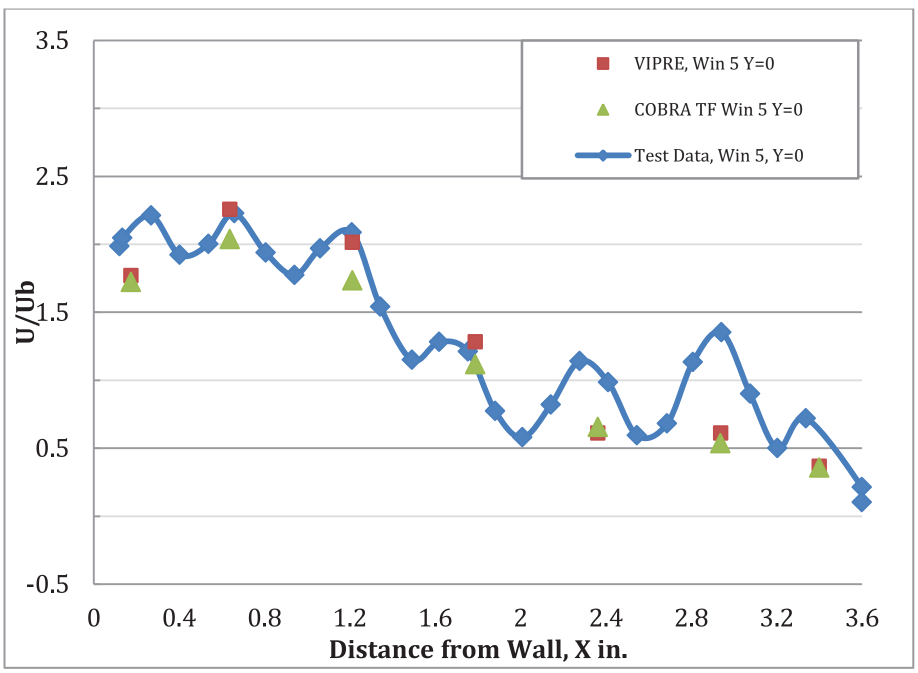

Figure 3. PNNL 2x6: Comparison of Velocities at Window 5 Elevation

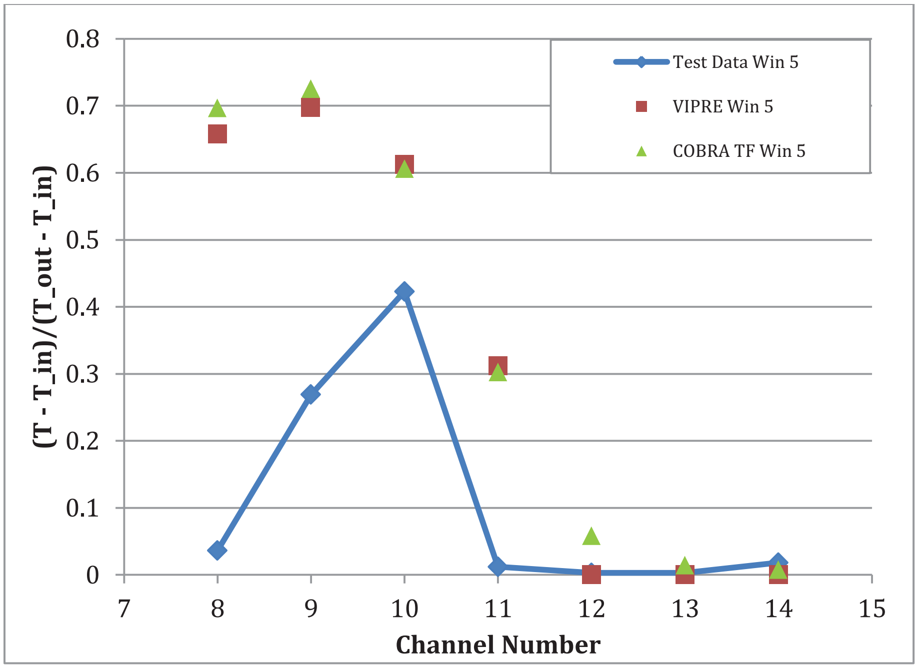

Figure 4. PNNL 2x6: Comparison of Temperature at Window 5 Elevation

Figure 5 and Figure 6 for the GE 3x3 test indicate that VIPRE-01 over-predicts exit equilibrium quality values on the corner channels and under-predicts in the center subchannels compared to the experimental data. CTF with the Void Drift option shows much closer agreement at lower quality levels, but seems to begin deviating at the higher quality levels.

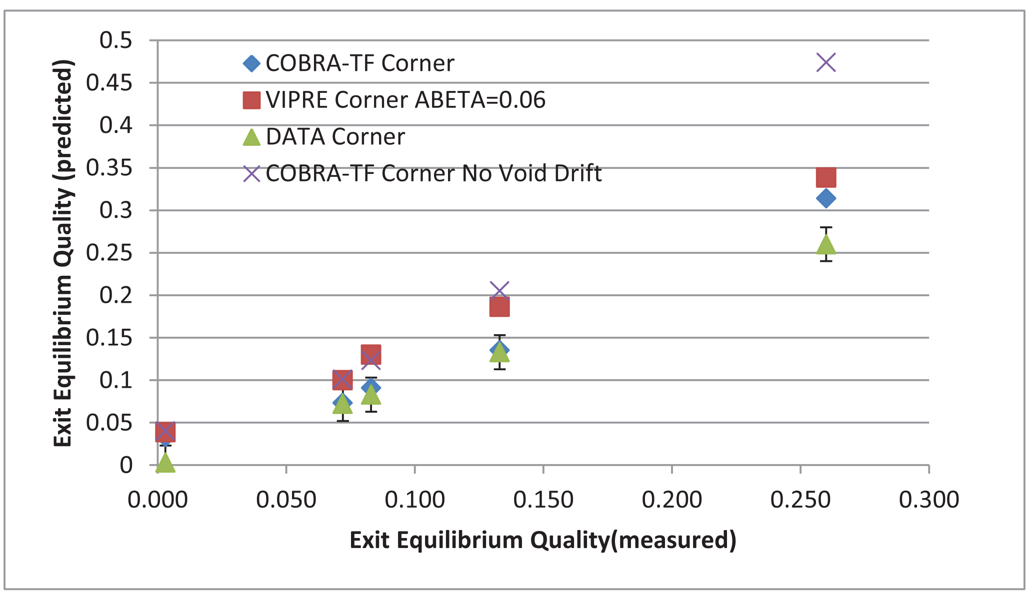

Figure 5. GE 3x3: Comparison of Exit Equilibrium Qualities (corner channel)

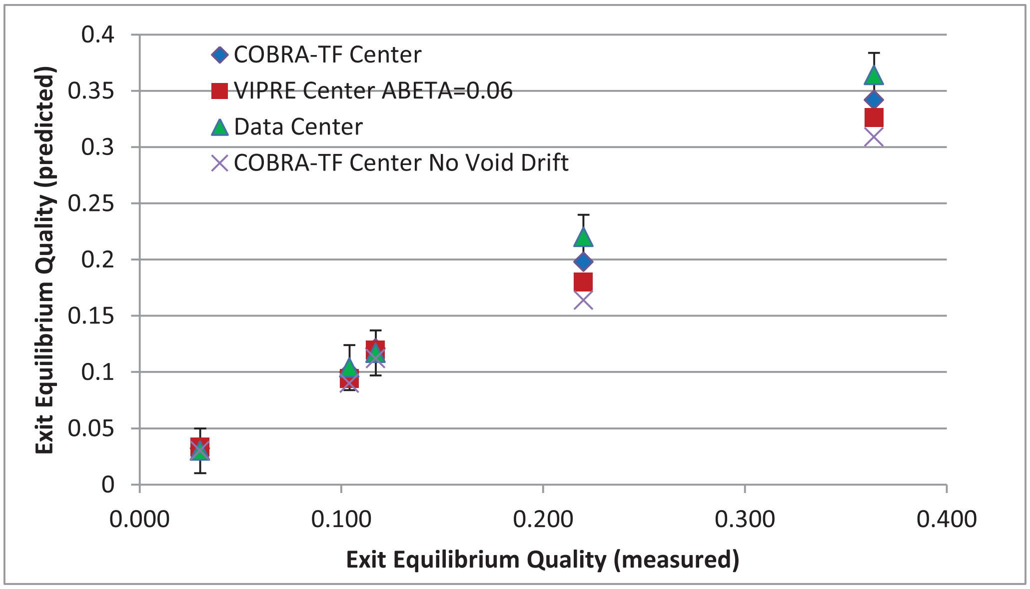

Figure 6. GE 3x3: Comparison of Exit Equilibrium Qualities (center channel)

Figure 7 and Figure 8 illustrate the mass flux values in a corner and center channel for the GE 3x3 test, and indicate that VIPRE-01 over-predicts exit mass flux values on the center channels and under-predicts in the corners compared to the experimental data. Both CTF and VIPRE-01 tend to over-predicts mass flux values for the lower range. Therefore, this phenomenon will require further investigation due to importance of this subject for NuScale plant condition.

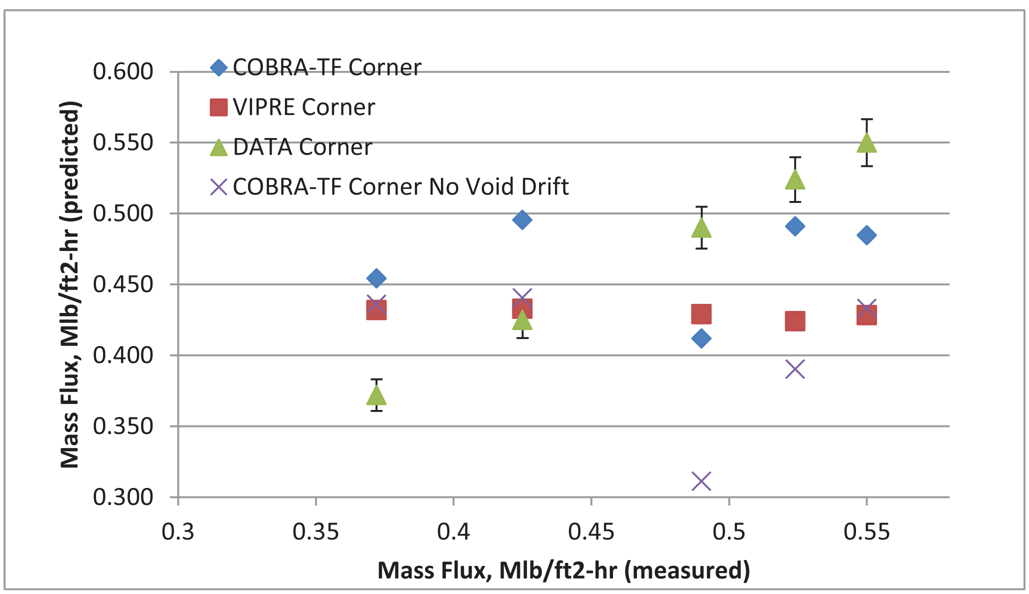

Figure 7. GE 3x3: Comparison of VIPRE and CTF results for GE 3x3 test (corner)

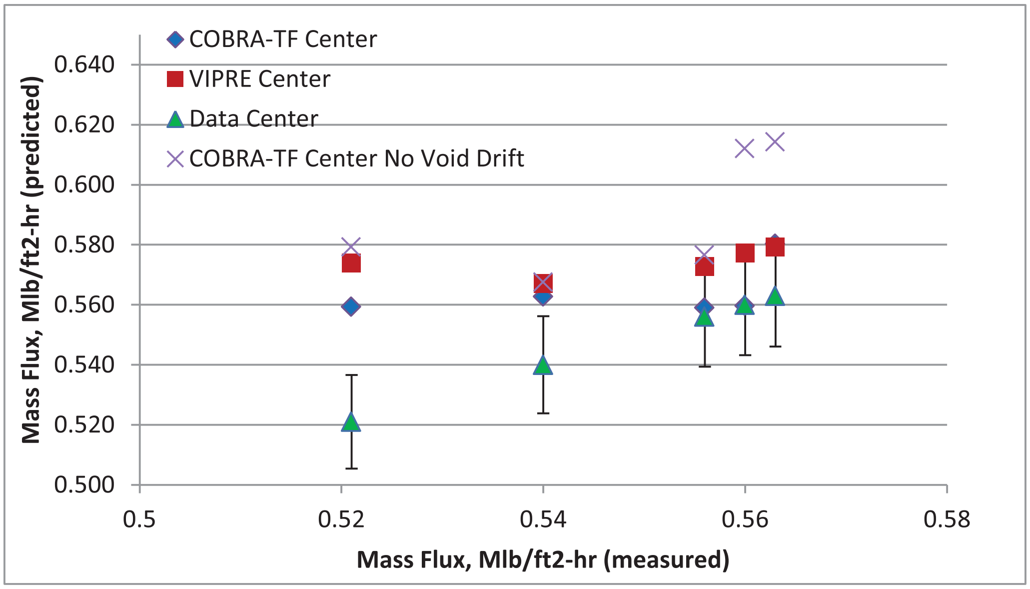

Figure 8. GE 3x3: Comparison of VIPRE and CTF results for GE 3x3 test (center)

The solution convergence of both codes was observed as a part of an effort to check the ability of both codes to converge in the presence of low pressure, or low/reverse flow. Based on the present test case results, both VIPRE-01 and CTF demonstrated the ability to handle low and reverse flow. However, an analysis of the output files shows that convergence for steady-state case was achieved after several hundred iterations and failed for some cases (e.g, VIPRE-01 calculations showed some convergence issues during scoping study when using turbulent mixing option, and CTF showed convergence issues for the low pressures). Therefore, this issue will require further investigation due to importance of this subject.

5 CONCLUSION AND FUTURE WORKS

Review of VIPRE-01 and CTF predictions of test results shows that both subchannel codes:

- demonstrate similar trends for velocity, exit equilibrium quality, and temperature. For example, both codes predict the effect of buoyancy on flow patterns and demonstrate similar trends in the case of single phase calculations (i.e., the codes temperature predictions are close);

- are able to converge at low inlet mass flux and pressure conditions but require an increased number of iterations in order to achieve the desired convergence level;

- perform what are considered to be likely accurate predictions of the physical processes under test conditions. However, there are some situations like mass flux over-predictions for the low flow range in case of GE 3x3 which require further investigation due to importance of the subject.

Most of the differences between subchannel code predictions and test results may be explained by the different flow and mixing modes. In particular, the GE 3x3 test model assessment suggest that Void Drift phenomenon plays an important role for subchannel mass and energy exchange in the test but this is not accounted for in VIPRE-01. Additional CTF results performed without the Void Drift option showed the importance of this mechanism in the lateral void redistribution process. Therefore, the Void Drift option may improve the VIPRE-01 predictions in two-phase flow situation. In the case of CTF, some improvements in the mixing model are needed for the lower mass flux ranges.

In summary, this work indicated that certain code models have to be further improved to address the operational domain of the NuScale reactor design.

6 REFERENCES

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