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Application of System Codes to Void Fraction Prediction in Heated Vertical Subchannels

Taewan Kim

Incheon National University, 119 Academy-ro, Yeonsu-gu, Incheon 22012, Republic of Korea.

Orcid: 0000-0001-9449-7502

Abstract

In general, the subchannel analysis has been conducted by means of dedicated subchannel analysis codes. However, the recent development of system codes with advanced two-phase flow model and three-dimensional components has helped more accurate and precise prediction of multiphase phenomena in nuclear reactor systems. The accurate prediction of the void fraction is one of the most important factors in subchannel analyses. This paper aims at evaluating the applicability of three different system codes to the prediction of the void fraction based on NUPEC experiment results employed for OECD/NRC PSBT benchmark. As a first step to the full scope analysis, analysis results for single channel experiments by using TRACE 5.0 Patch 3, MARS-KS 1.3, and RELAP5/MOD3.3 Patch 4 are presented in this paper. The result indicates that all codes slightly over-predict the void fraction compared to the experimental results in general and no significant discrepancies between the codes are observed.

Keywords: Single channel, Void fraction, RELAP5, MARS-KS, TRACE.

1. INTRODUCTION

The prediction of the void fraction in a channel has been of interest in nuclear field since the void fraction in the reactor core is highly connected to the reactor safety. In general, the void fraction in the core has been analyzed by means of dedicated subchannel analysis codes such as COBRA-TF, VIPRE-02, MATRA, FLICA-OVAP, and so on. However, since those codes more focus on the steady state or design condition than anticipated transients and accidents, it is limited to utilize the subchannel analysis codes for the detailed evaluation of the core thermal hydraulic condition during the transient and accident in general.

Meanwhile, many system codes have been developed and improved in past decades with advanced two-phase flow model and some of them include a capability of multi-dimensional analysis for detailed analysis of complicated component such as the reactor pressure vessel. Therefore, the detailed evaluation of the core thermal hydraulic condition during the accidents can be obtained by using advanced system codes if the applicability of the system codes to such a detailed analysis is justified.

This study aims at evaluating the applicability of the advanced system codes to the subchannel analysis. Before moving to multi-channel cases, single channel applications have been analyzed by means of three-different system codes in order to evaluate the performance and accuracy of those codes in simple geometry. The assessment has been conducted against experiment performed at NUPEC experimental facility employed for OECD/NRC PSBT benchmark [3].

2. DESCRIPTION OF EXPERIMENT

2.1. NUPEC Facility

Figure 1 shows the NUPEC test facility, where the experiments for the PSBT benchmark were carried out. This facility contains a high pressure and high temperature recirculation loop, a cooling loop, and instrumentation and data acquisition systems. To represent a single subchannel and a complete rod bundle, different subchannels were constructed. The design temperature and pressure are 19.2 MPa and 362 oC respectively. The benchmark consists of two phases: phase I for void distribution benchmark and phase II for DNB benchmark. The detailed description of the test facility can be found in reference [3].

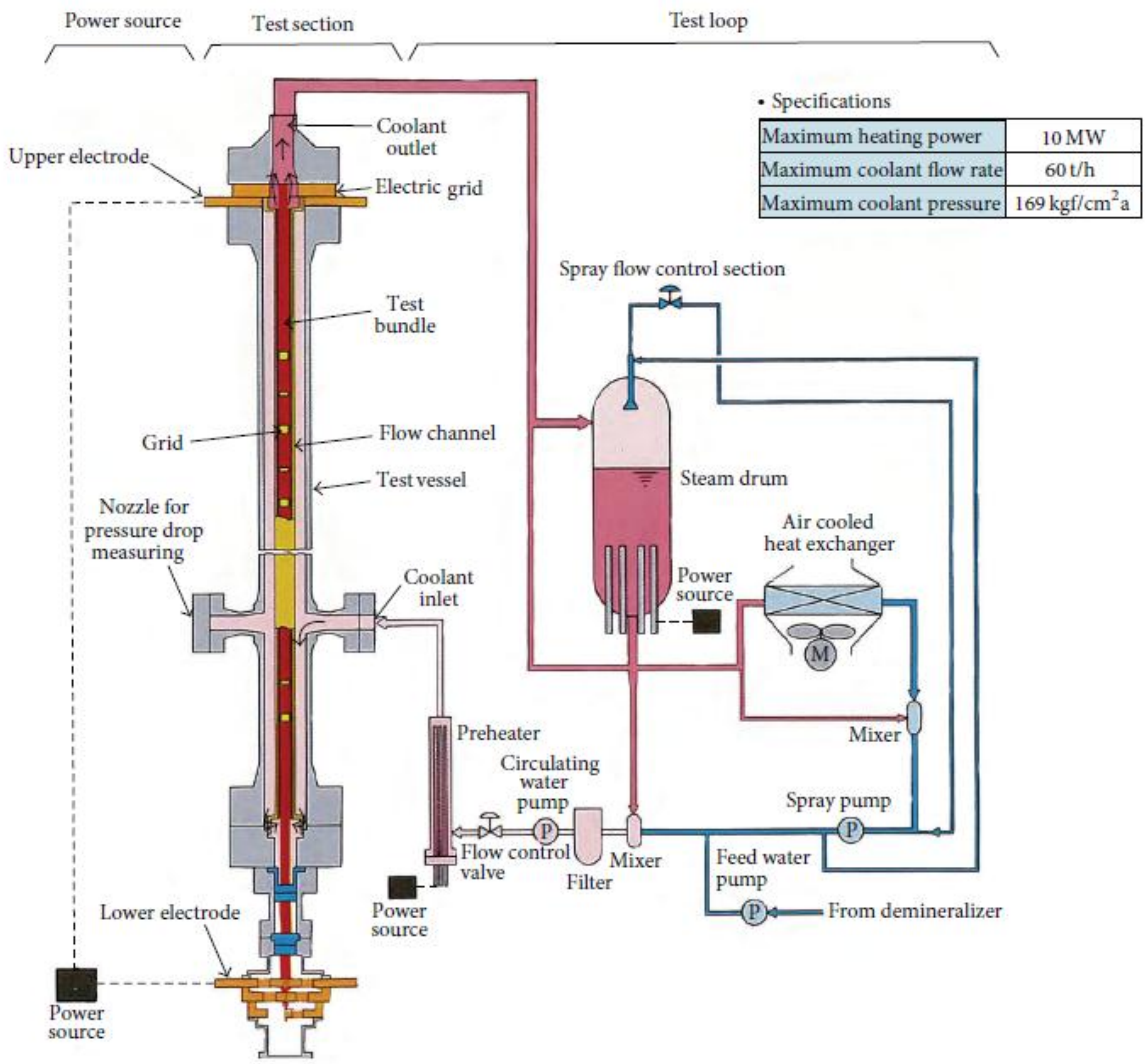

Figure 1: System Diagram of NUPEC PWR Test Facility [3]

Single Channel Experiments

To measure the void distribution a series of steady-state experiments were carried out. For the single channel experiment four different subchannels were considered which are shown in Table 1 and Figure 2. Figure 2 depicts the test section for central subchannel void distribution measurement. The effective length is 1555 mm, and the cross-section where the void measurements were performed is at 1400 mm from the bottom of the heated section.

Table 1: Geometry and power shape for each test section [3]

Item	Data			
Assembly (Subjected subchannel)	S1	S2	S3	S4
Subchannel type	Center (Typical)	Center (Thimble)	Side	Corner
Number of heaters	4×1/4	3×1/4	2×1/4	1×1/4
Axial heated length (mm)	1555	1555	1555	1555
Axial power shape	Uniform	Uniform	Uniform	Uniform

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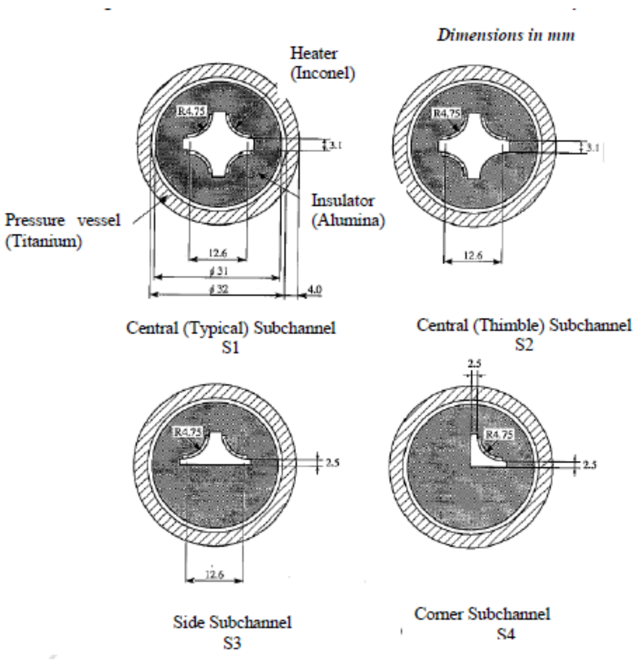


Figure 2: Cross-sectional View of Subchannel Test Assembly [3]

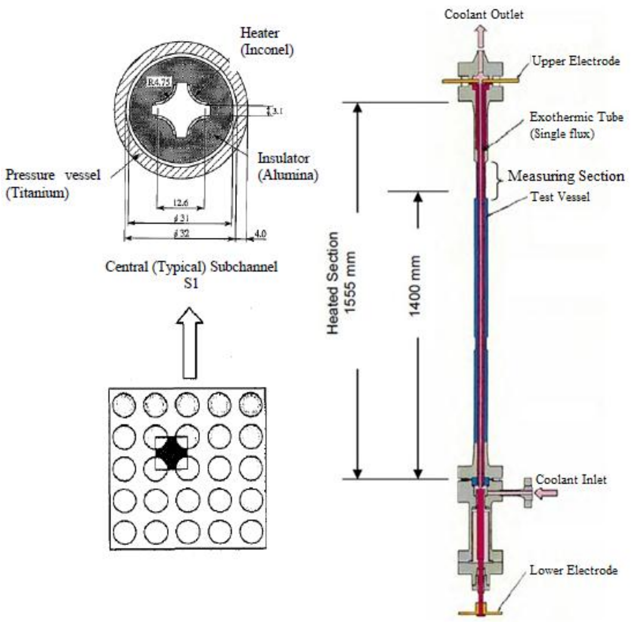


Figure 3: Cross-sectional View of Central (Typical) Subchannel Test Assembly [3]

BEST ESTIMATE CODE SIMULATIONS

Thermal Hydraulics Codes

TRACE v5.0 Patch 3

TRACE v5.0 Patch 3 is the latest version best-estimate thermal-hydraulic system code, which is developed by US NRC for analyzing steady-state and transient neutronic/thermal-hydraulic behavior of light water reactors. The basic TRACE thermal–hydraulic model consists of a set of six conservation equations for the liquid and gas fields [6]. In the code, the Lahey's model is employed to model subcooled boiling heat transfer. A single-phase heat transfer coefficient is modeled by Gnielinski correlation, two-phase multipliers by Aggour et al. and Rezkallah and Sims are employed for bubbly/slug regime.

MARS-KS 1.3

The MARS-KS (Multi-dimensional Analysis of Reactor Safety) code developed by KAERI for a multi-dimensional and multi-purpose realistic thermal-hydraulic system analysis of light water reactor transients. The code backbones are built through unification and restructuring the RELAP5/MOD3.2.1 and COBRA-TF1 (Coolant Boiling in Rod Arrays, Two-Fluid version) codes [7]. Thus, the MARS-KS code has two different hydrodynamic models for two-phase flows. The flow regime maps of the code have been developed to control the use of constitutive relation correlations based on the work of Taitel, Dukler and Ishii. For pre-CHF heat transfer, the modeled regimes of the bubbly, slug, annular-mist were utilized by Vince and Lahey. For post-CHF heat transfer as suggested by Ishii, the bubbly, slug, and annular-mist regimes are transformed to the inverted annular, inverted slug, and mist regimes, respectively.

RELAP5/MOD3.3 Patch 4

The RELAP5 code was developed at the Idaho National Engineering Laboratory is one of the most advanced analysis codes which provide best-estimate predictions of postulated accidents and transients in light water reactor systems. The code features a two-phase, two-fluid non-equilibrium hydrodynamic model with many generic component models and special process models. In the code, a heat transfer mode transition map has been developed to make sure of a smooth transition between the two adjacent modes. The full details of the transition logic used in the code are found in the computer code manual [8].

Thermal Hydraulics Codes Modeling

The same optimized nodalization of pipe depicted in Figure 4 was applied for three codes to simulate the void fraction in the single channel of PSBT benchmark. The heated length was divided into 25 nodes with measure point located in the center of node 23. In the coolant side, the model consists of an inlet time dependent volume that supply the mass flow boundary condition and temperature and an outlet time dependent volume controls the pressure boundary condition. A heat structure was used which is worked as a rod linked with power component to give a constant amount of heat to the coolant. The nodalization of power component and heat structure is similar to pipe nodalization in length and node positions. In figure 3, it can be seen how the model looks like. Table 2 shows the input parameters for simulation regarding to geometries of four cases typical, thimble, side, and corner.

Table 2: Input parameters for simulation

	Typical (S1)	Thimble (S2)	Side (S3)	Conner (S4)
Number of heaters (1/4)	4	3	2	1
Axial heated length (mm)	1555	1555	1555	1555
Axial power shape	Uniform	Uniform	Uniform	Uniform
Flow area (mm^2)	107.098	107.098	68.464	42.592
Heated perimeter (mm)	29.845	22.384	14.923	7.461
Wetted perimeter (mm)	54.645	54.645	44.923	33.161
Outer radius (mm)	4.75	3.5625	2.3751	1.1875
Inner radius (mm)	3.9	2.7125	1.5251	0.3374

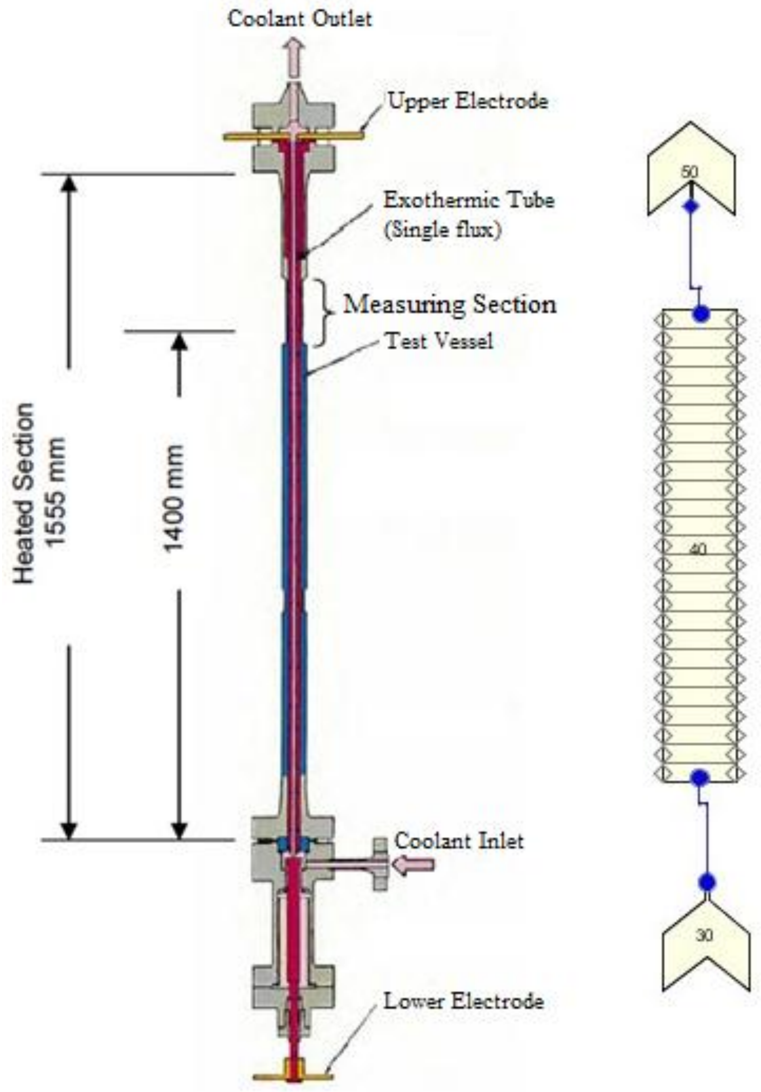
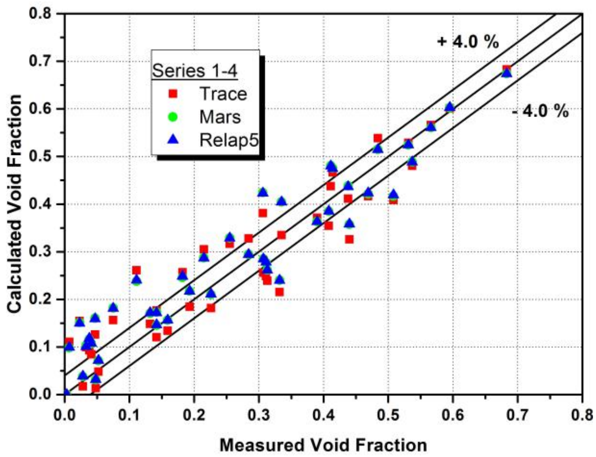


Figure 4: Pipe Nodalization. [3]

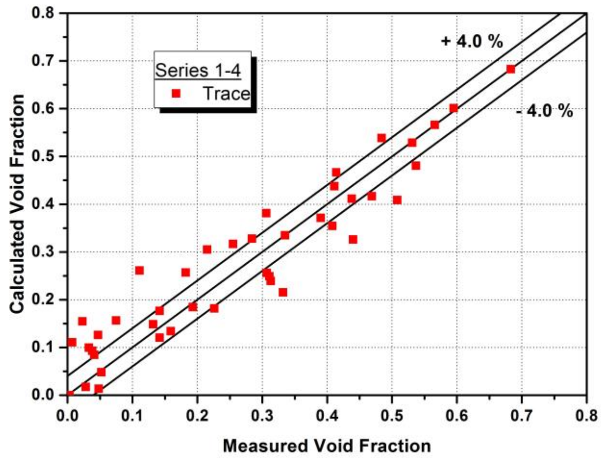
RESULTS AND DISCUSSION

Calculation Results

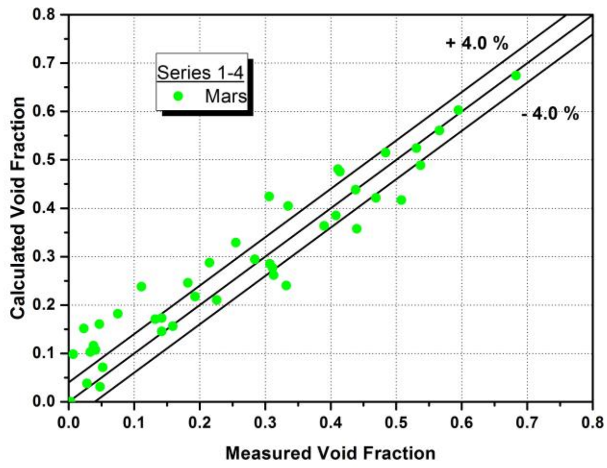
In the experiments, different initial conditions were employed for pressure, temperature, mass flow rate, and heater power. Three codes run for 16, 12, 8, and 8 different initial conditions for test series S1, S2, S3, and S4, respectively, in this analysis. The results of void fraction calculation for series 1 to 4 are depicted in Figure 5. The predictions from codes are generally acceptable, where the calculated value is not too far from range of -4% to 4%. However, codes overestimated when the void fractions are smaller than 0.3. Besides, data from TRACE code are probably lower than the one from MARS-KS and RELAP5. This indicated the differences in boiling correlations of each code. MARS-KS and RELAP5 shows the results almost the same to each other. The consistence is because one-dimensional module of MARS-KS has been developed on the basis of RELAP5 and the latest version of RELAP5 includes the same boiling model as before.



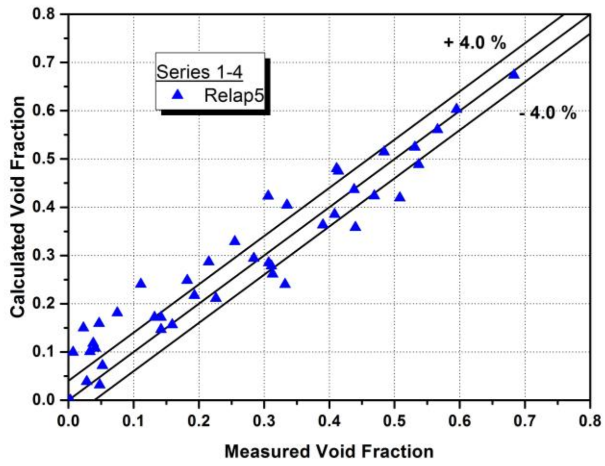
(a) TRACE, MARS-KS, and RELAP5



(b) TRACE



(c) MARS-KS



d) RELAP5

Figure 5: Results from TRACE, MARS-KS, and RELAP5 for series 1 to 4

Statistical Analysis

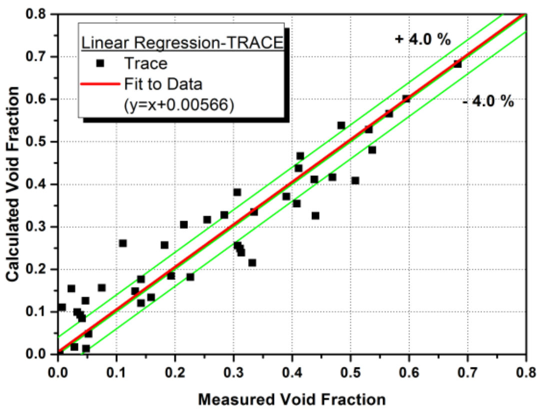
Two statistical analyses were conducted to assess the correlation between calculated results and experimental data quantitatively as well as to have a comparable view among code simulations. Linear regression method approaches the relationship between experimental data and calculated data. The root mean square values were calculated to see the accuracy of each system code.

Linear Regression

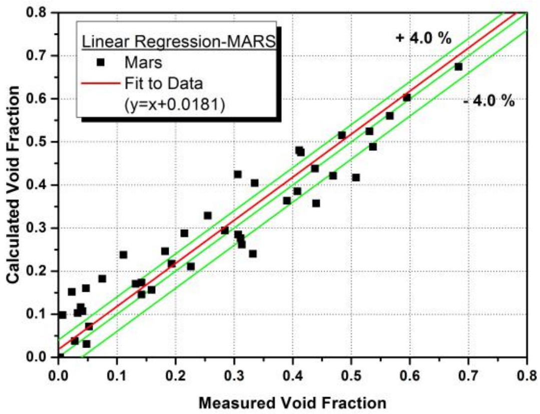
The linear regression method has been employed to find out a general trend of the prediction by each code. Based on the calculation data from TRACE, MARS-KS, and RELAP5, a regression function was developed for each code, as depicted in Figure 6. A slope of 1.0 was applied for three code calculation data to estimate the bias of prediction results from experiments. Table 3 shows the regression results. As listed in the table, the adjusted R2 for the developed linear regression function is 0.87 for all codes. The average void fraction results in codes are biased from the measurement values as shown in Figure 6. The predictions by TRACE, MARS-KS, and RELAP5 slightly over-estimate experiment data by 0.56%, 1.81% and 1.82%, respectively. The mean absolute errors are figured out for code calculations with respective values of 5.29%, 5.08%, and 5.07% for TRACE, MARS-KS, and RELAP5. According to 4% absolute void fraction in measurement, the errors by the codes is slightly higher than experimental error.

Table 3. Summary of fits for codes calculation results

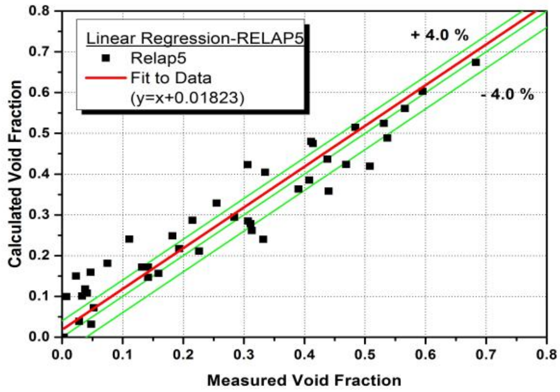
Code	Intercept		Slope		Statistics
	Value	Error	Value	Error	Adj. R-Square
TRACE	0.00566	0.01004	1	--	0.87024
MARS-KS	0.01801	0.00958	1	--	0.87569
RELAP5	0.01823	0.00954	1	--	0.87635



(a) TRACE



(b) MARS-KS



(c) RELAP5

Figure 6: Fits for void fraction with slope of 1.

Root mean square (RMS)

A comparable view of code simulation results were implemented by using the root mean square (RMS) method. Figure 7 shows the comparison among RMS values with 0.06531, 0.06463, and 0.06449 for TRACE, MARS-KS, and RELAP5, respectively. Even though the RMS value of TRACE is slightly higher than the RMS values by other codes, basically, it can be concluded that there is no significant discrepancy in accuracy between three different system codes.

Table 4: RMS errors of code calculation

Code	Root Mean Square	Mean	Standard Deviation	Mean Absolute Deviation
TRACE	0.06530	-0.00566	0.06583	0.05292
MARS-KS	0.06463	-0.01801	0.06281	0.05088
RELAP5	0.06448	-0.01823	0.06259	0.05071

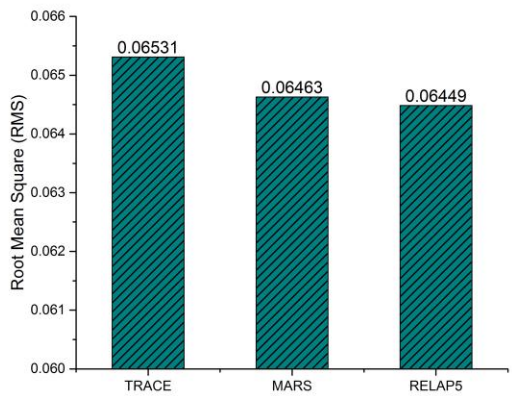


Figure 7: Root mean square values for TRACE, MARS-KS, and RELAP5

CONCLUSIONS

The void fraction in single channel was calculated by using three system codes RELAP5, TRACE, and MARS-KS. In order to assess the accuracy of the calculation by each system code quantitatively, the calculation result was analyzed by using the linear regression and the root mean square methods. From the analysis, it was found that in general all system codes predict the void fraction consistently. In addition, it was found that the codes slightly over-estmiate the experiment and the error determined by the RMS method indicates the system code prediction can produce slightly higher error than one specified by experiment. However, in order to justify the applicability of the system codes to the channel analysis concretely, it is required to compare the results from dedicated subchannel analysis codes which might be one of the next studies.

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