VOL. 12, NO. 21, NOVEMBER 2017 ISSN 1819-6608
ARPN Journal of Engineering and Applied Sciences

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ANALYSIS OF DEPARTURE FROM NUCLEATE BOILING IN BUNDLE USING A SUBCHANNEL ANALYSIS CODE

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ABSTRACT

The accurate prediction of the departure from nuclear boiling is critical in securing the safety of boiling systems. Especially, the departure from nucleate boiling has a particular importance in reactor core of a nuclear power plant system since the phenomenon itself can indicate the soundness of the nuclear fuel cladding against the failure. The departure from nucleate boiling in the core has been analyzed by means of subchannel analysis codes. Thus, it is of importance to assess the prediction capability of subchannel analysis codes for departure from nucleate boiling against experimental data. In this study, the subchannel analysis code, FLICA4, has been assessed against bundle experiments conducted at NUPEC experimental facility. The assessment has been conducted for steady-state cases and the results indicate that FLICA4 predicts slightly lower departure from nucleate boiling power. Considering the accuracy of Groeneveld look-up table and the uncertainties in the experimental data, it is concluded that the prediction by FLICA4 is conservative and acceptable. An assessment of the critical heat flux models of FLICA4 has been carried out. The Groeneveld look-up table and the W3 correlation have been examined. The results reveal that the Groeneveld look-up table predicts more conservative departure from nucleate boiling power with better accuracy than the W3 correlation. Therefore, it is recommended to employ the Groeneveld look-up table to estimate the critical heat flux.

Keywords: departure from nucleate boiling, critical heat flux, FLICA4, bundle.

1. INTRODUCTION

The accurate prediction of the departure from nuclear boiling (DNB) is critical in securing the safety of boiling systems. Especially, the DNB has a particular importance in reactor core of a nuclear power plant system since the phenomenon itself can indicate the soundness of the nuclear fuel cladding against the failure. The DNB in the core has been analyzed by means of subchannel analysis codes. Thus, it is of importance to assess the prediction capability of subchannel analysis codes against experimental data.

Meanwhile, OECD/NEA and United State Nuclear Regulatory Commission (US NRC) organized an international benchmark, namely OECD/NRC PSBT benchmark, in order to encourage advancementin subchannel analyses of fluid flow in rod bundles [1]. The benchmark was aimed at assessing the capabilities of systemcodes, subchannel codes and CFD codes for the prediction of detailed void distributions in subchannels, including DNB, on the basis of experimental data measured at a full scale prototypicalrod bundle of pressurized water reactors. The experiment for the benchmark was carried out at NUPEC experimental facility in early 1980s and the results cover a wide range of thermal hydraulic conditions.

This study aims at assessing the predictability of a subchannel analysis code against experimental data provided in the frame work of OECD/NRC PSBT benchmark, especially from the DNB point of view. The analysis has been carried out by using subchannel analysis code, FLICA4 [2]. Since the DNB in the reactor core has bigger importance in design state, the steady-state DNB experiments has been analyzed in this study.

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^{o}C 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].

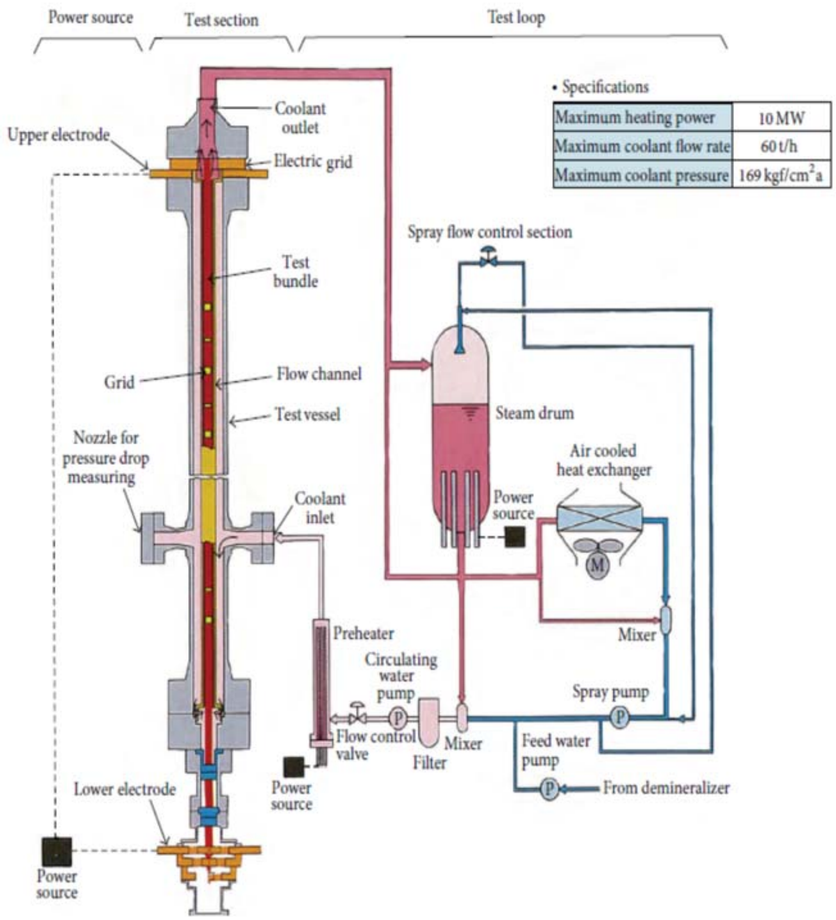

Figure-1. System diagram of NUPEC PWR test facility [3].

2.2. Test assembly

As listed in Table-1, five different assemblies are employed for the steady-state DNB experiments in the PSBT benchmark PhaseII. All assemblies are based on 17x17 fuel type and have a rod array of 5x5, except for assembly A3 which is 6x6. In case of assembly A8, a thimble rod is located in the center of each assembly. All assemblies can be classified into three groups according to the number and location of spacers, as listed in Tables2 and3. Three different types of spacer are included in the test assembly. Two axial power profiles are considered in this benchmark: uniform and cosine. In total four radial power distributions are employed in the benchmark and they are depicted in Figure-2.

Table-1. Test assemblies for DNB benchmark [3].

Assembly	Reference fuel type	Rods array	Type of cell	Power distribution	
				Radial	Axial
A0	17x17M	5x5	Typical cell	A	Uniform
A2			Typical cell	A	Uniform
A3		6x6	Typical cell	D	Uniform
A4		5x5	Typical cell	A	Cosine
A8			Thimble cell	B	Cosine

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Table-2. Specifications of assembly A0, A2, and A3 [3].

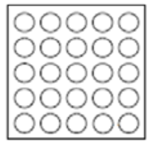
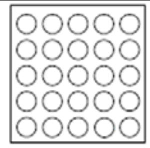
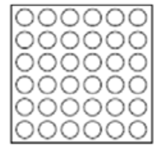
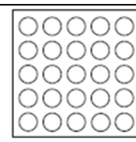
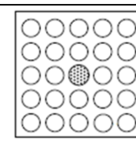
Item	Data		
Assembly	 **A0**	 **A2**	 **A3**
Heated rod outer diameter (mm)	9.5	9.5	9.5
Thimble rod outer diameter (mm)	-	-	-
Heated rod pitch (mm)	12.60	12.60	12.60
Axial heated length (mm)	3658	3658	3658
Flow channel inner width (mm)	64.9	64.9	77.5
Radial power shape	A	A	D
Axial power shape	Uniform	Uniform	Uniform
Number of mixing vane spacers	5	7	7
Number of no mixing vane spaces	2	2	2
Number of simple spacers	6	8	8

Table-3. Specifications of assembly A4 and A8 [3]

Item	Data	
Assembly	 **A4**	 **A8**
Heated rod outer diameter (mm)	9.5	9.5
Thimble rod outer diameter (mm)	-	12.24
Heated rod pitch (mm)	12.60	12.60
Axial heated length (mm)	3658	3658
Flow channel inner width (mm)	64.9	64.9
Radial power shape	A	B
Axial power shape	Cosine	Cosine
Number of mixing vane spacers	7	7
Number of no mixing vane spaces	2	2
Number of simple spacers	8	8

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0.85	0.85	0.85	0.85	0.85
0.85	1.00	1.00	1.00	0.85
0.85	1.00	1.00	1.00	0.85
0.85	1.00	1.00	1.00	0.85
0.85	0.85	0.85	0.85	0.85

(A) Type A

0.85	0.85	0.85	0.85	0.85
0.85	1.00	1.00	1.00	0.85
0.85	1.00	0.00	1.00	0.85
0.85	1.00	1.00	1.00	0.85
0.85	0.85	0.85	0.85	0.85

(B) Type B

1.00	1.00	0.25	0.25	0.25
1.00	1.00	1.00	0.25	0.25
1.00	1.00	0.25	0.25	0.25
1.00	1.00	1.00	0.25	0.25
1.00	1.00	0.25	0.25	0.25

(C) Type C

0.85	0.85	0.85	0.85	0.85	0.85
0.85	1.00	1.00	1.00	1.00	0.85
0.85	1.00	1.00	1.00	1.00	0.85
0.85	1.00	1.00	1.00	1.00	0.85
0.85	1.00	1.00	1.00	1.00	0.85
0.85	0.85	0.85	0.85	0.85	0.85

(D) Type D

Figure-2. Radial power distribution [3].

3. FLICA4 MODELING

Thermal hydraulic models for the FLICA4 calculation are generated on the basis of the information of the geometry and the power distribution. Since the geometry and radial power distribution allow generating symmetric models, 1/8 symmetry models were employed for bundle tests in Phase-I. However, in Phase II, it is impossible to have 1/8 symmetry in general due to radial power distribution C. Since radial power distribution C allows implementing 1/2 symmetry only, in order to be consistent, all models are generated by using 1/2 symmetry as depicted in Figures-3 and -4. The models are nodalized with 100 axial nodes.

The Chexal-Lellouche model [4] was employed as a drift-flux model and a value of 7.5E-4 was imposed for the recondensation coefficient, KV0. The multipliers for turbulent conductivity and viscosity, Kt and Mt, were set to 0.01 based on results from Phase I. The pressure drop by the spacers was considered by means of the singular pressure drop model in FLICA4. For DNB calculations, the W3 correlation [5] and the Groeneveld look-up table [6] were employed. However, due to limit in application ranges, the W3 correlation cannot be used for all cases in Phase II. A sensitivity analysis for both correlations, which will be explained later, indicates that the DNB power predicted by the Groeneveld look-up table is slightly lower than the result from the W3 correlation. However, no significant discrepancy was observed. Considering the robustness and conservatism, it was decided to employ the Groeneveld look-up table for the Phase II DNB analysis.

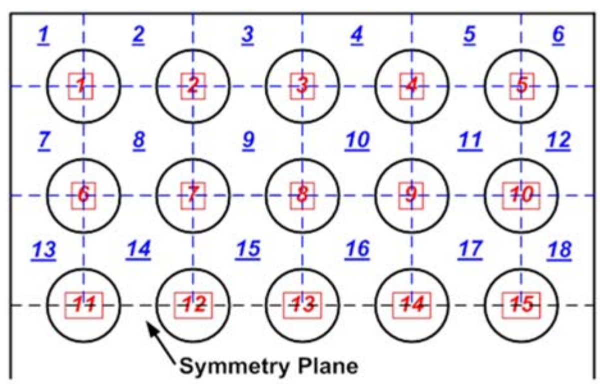

Figure-3.1/2 Symmetry model of a 5x5 assembly.

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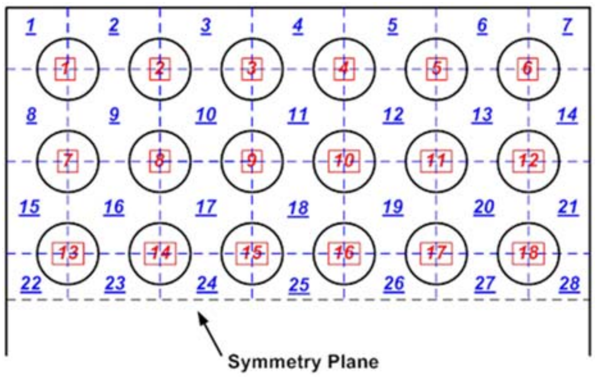

Figure-4. 1/2 Symmetry model of a 6x6 assembly.

4. STEADY-STATE DNB ANALYSIS

4.1. DNB analysis Results

The steady-state DNB analyses were conducted for test series 0, 2, 3, 4, 8, and 13 as indicated in Table-4.

In the experiment, the surface temperatures of each heater rod were measured by thermocouples attached at the inner surface of each heater rod. The heater power was increased gradually by fine steps to the vicinity of DNB power which was estimated by preliminary analyses. The occurrence of DNB is confirmed by a rod temperature rise of more than 11 ºC. Then, the DNB power is defined as the power corresponding to the step just before the step where the temperature increased.

In the FLICA4 analysis, it was employed as an indicator for the occurrence of DNB the minimum DNB ratio (MDNBR) defined by a ratio of the critical heat flux (CHF) predicted by a given correlation to the heat flux of each axial node of each heater rod. The occurrence of DNB is confirmed when the MDNBR is less than unity. The Groeneveld CHF look-up table was employed for this analysis and a sensitivity analysis with the W3 correlation was performed, which will be explained in section 4.2.

The results from all calculations are plotted in Figures5 to 10, together with the results of participants of the PSBT benchmark from other organizations [7]. In general, FLICA4 predicts lower DNB power than one measured in the experiment, i.e. the result is conservative. The same tendency was observed from the results of most participants from other organizations. The mean absolute error of the DNB power prediction by FLICA4 is 10.1 %. Consequently, a comparison with the results of other participants indicates that FLICA4 predicts the DNB Power a little conservatively but as accurate as other state-of-the-art subchannel analysis codes.

Table-4. Test series for steady-state DNB analysis.

Test series	Test section	Assembly
0	5x5	A0
2		A2
3	6x6	A3
4	5x5	A4
8		A8
13		A4

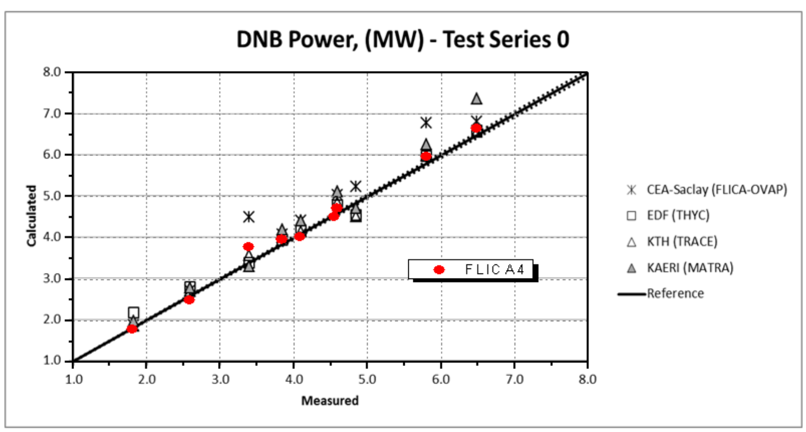

Figure-5. Results of test series 0.

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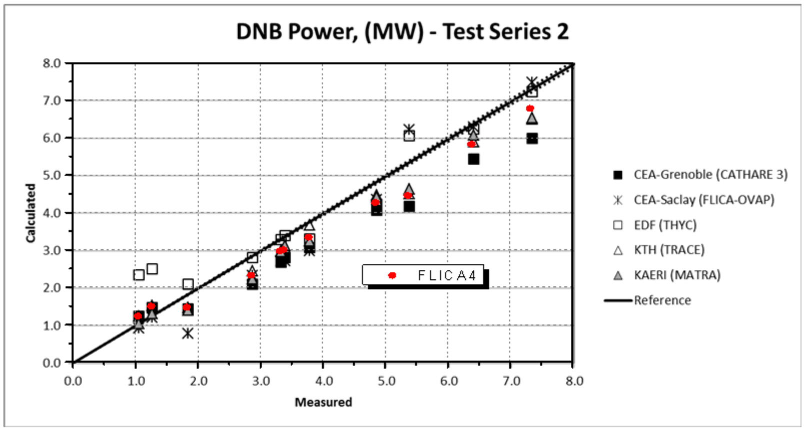

Figure-6. Results of test series 2.

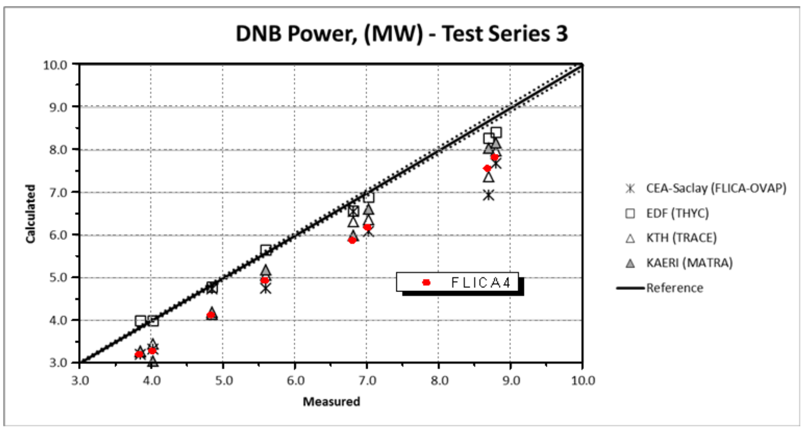

Figure-7. Results of test series 3.

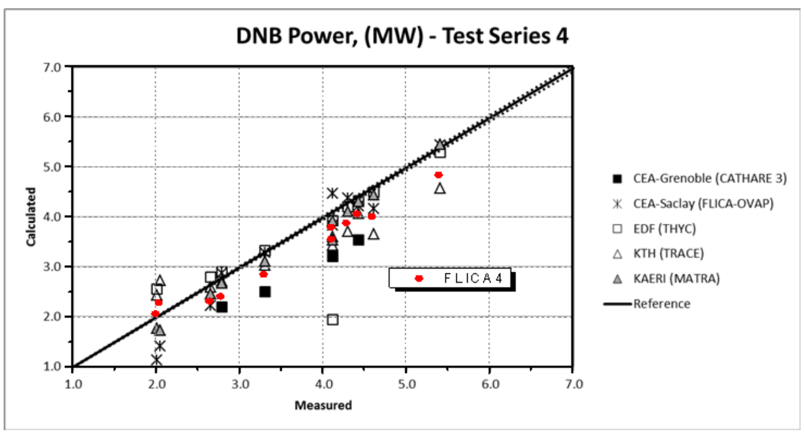

Figure-8. Results of test series 4.

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ARPN Journal of Engineering and Applied Sciences

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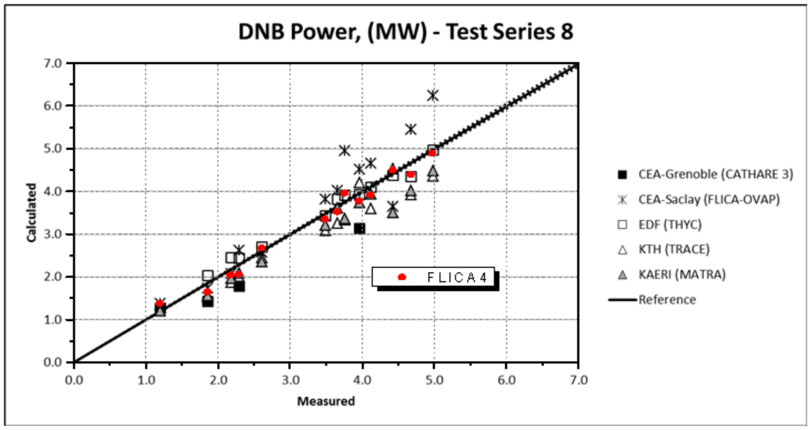

Figure-9. Results of test series 8.

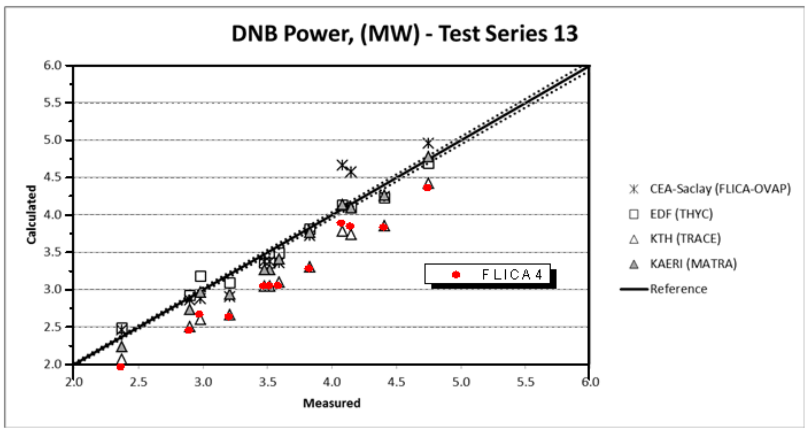

Figure-10. Results of test series 13.

4.2. Assessment of CHF correlations

An assessment of CHF correlations in FLICA4 has been carried out against test series 8 with a thimble rod. It was examined two CHF correlations included in FLICA4, Groeneveld loop-up table and W3 correlation. The Groeneveld look-up table was developed jointly by AECL (Canada) and IPPE (Russia), and it covers very wide range of applicability. Based on large validation works, it is known that the Groeneveld look-up table can predict the CHF data with overall root-mean-square (RMS) error of 7.82 %. The W3 correlation is very widely used correlation for DNB in PWR fuel bundle, especially design purpose. Although the W3 correlation itself has been developed under uniform heat flux condition, the model includes a correction factor for non-uniform heat flux condition such as cosine.

For the assessment, test series 8 has been analyzed by using each correlation. The test series was selected to figure out the predictability of each correlation under asymmetric conditions which is more realistic considering the actual design of reactor core. As depicted in Figure-11, it was found that the Groeneveld look-up table predicts lower DNB power than the W3 correlation which indicates the conservatism of the Groeneveld look-up table. In addition, some cases in test series 8 could not analyzed by using W3 correlation because of convergence problem. Therefore, it is recommended to use the Groeneveld look-up table rather than the W3 correlation in DNB analysis, especially for design purpose.

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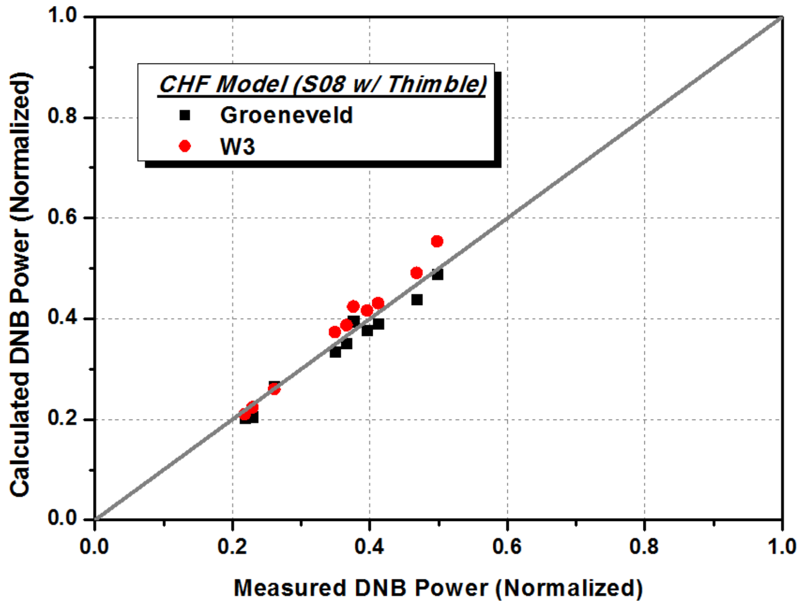

Figure-11. Assessment of CHF correlation.

5. CONCLUSIONS

The steady-state DNB experiments have been analyzed by using the subchannel analysis code, FLICA4. Based on the analysis results, the following conclusions can be drawn:

- Results from steady-state DNB analysis indicate that FLICA4 predicts slightly lower DNB Power with a mean absolute error of 10.2 %. This reveals that FLICA4 predicts the occurrence of DNB slightly earlier than actual so that, from the safety point of view, the result from FLICA4 can be considered to be conservative. Considering the accuracy of Groeneveld look-up table and the uncertainties in the experimental data, it is concluded that the prediction of the DNB power by FLICA4 is conservative and acceptable.
- An assessment of the CHF models of FLICA4 has been carried out. The Groeneveld look-up table and the W3 correlation have been examined. The results reveal that the Groeneveld look-up table predicts more conservative DNB power with better accuracy than the W3 correlation. Therefore, it is recommended to employ the Groeneveld look-up table to estimate the CHF.

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