Transactions of the Korean Nuclear Society Spring Meeting
Jeju, Korea, May 23-24, 2019

CHF Prediction Evaluation for START Sub-channel Code

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1. Introduction

Critical Heat Flux (CHF) is the value of heat flux at which heat transfer from fuel rod to coolant is suddenly deteriorated due to formation of vapor film. This causes large increase in fuel rod surface temperature and can lead to fuel rod damage. CHF is a limiting thermal phenomenon in nuclear power reactors and is a complex function of geometry and flow conditions. Various correlations such as EPRI, BIASI, CISE-4, W3, to mention a few, have been utilized to determine the CHF. Based on database of many CHF experiments, another approach is to use CHF lookup table (LUT). There have been different versions of CHF LUT i.e. 1986, 1995 and 2006. These LUTs are developed for a wide range of geometrical and flow conditions. In this work, in-house code Steady and Transient Analyzer for Reactor Thermal Hydraulics, START [1] has been equipped with 2006 Groeneveld CHF LUT [2] for LWR conditions. Preliminary validation exercise has been carried out against PWR sub-channel and bundle tests (PSBT) [3] database. For both steady state and transient cases, CHF has been predicted for different test conditions. Comparison with experimental values is carried out and is presented.

2. Methods and Results

The START code is an in-house developed code to perform sub-channel thermal-hydraulic analyses for LWRs [1]. The START code is written in Fortran 90 in a modular fashion. Special emphasis is on fast execution to perform coupled neutron physics/thermal-hydraulic analysis in a reasonable time. OpenMP parallelization is applied to several parts of the code. Good parallel efficiency of almost 80% is achieved. Whole core calculations for a large size PWR (241 assemblies of 17x17 matrix) takes approximately one minute on 40 cores (2.40 GHz) Intel Xeon Gold 6148 CPUs.

The START code is based on homogeneous two-phase model. Basic conservation equations (mass, momentum and energy), based on sub-channel formulation, are solved using marching algorithm. Newton-Raphson iterations determine pressure drop for axial and radial pressure drop used in axial and lateral momentum equations. Time-dependent solution is based on an implicit scheme. The START code solution has been validated against PSBT [1]. Capability of code to predict quality and void fraction in different geometrical configurations has been carried out. Both steady-state and transient scenarios have been modeled by the code and compared with experimental data. Good agreement is seen between calculated and experimental results [1]. Various correlations and model used in the START code are given in Table 1.

Table 1: Correlations and models used in the START code

Parameter	Correlation
Two-phase friction multiplier	Armand Correlation
Grid spacer pressure drop	K. Rehme Model
Sub-cooled boiling	Lellouche
Void Fraction	Armand-Massena
HTC (Single phase/subcooled and saturated nucleate boiling)	Dittus-Boelter/ Dittus+Thom

In order to check the ability of CHF prediction by START code, 2006 Groeneveld CHF LUT has been implemented. Local conditions are used to determine the CHF value from LUT. If the prevalent conditions correspond to a point that lies between the table values, trilinear interpolation is carried out, as depicted in Fig. 1.

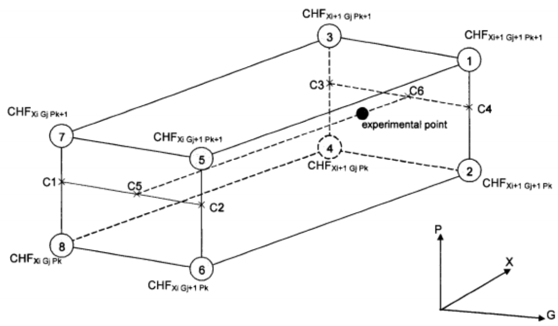

Fig. 1: Trilinear interpolation for LUT

Relevant correction factors such as sub-channel or tube cross-section factor (K1), grid spacer factor (K3) and heated length factor (K4) have been used in current analyses. Classifying on basis of geometrical details, various bundles have been given code names in PSBT database. All of the bundles considered for this validation effort at 5 x 5. They may differ in axial/radial power profile, grid spacer number and location, and/or presence of thimble rod. Wide range of conditions is studied in PSBT for CHF prediction. For example, pressure range for different tests is from 5.1 to 16.65 MPa. Similarly inlet temperature variation is between 429 to 596 K and mass flux range is 328 to 4940 kg/m^2-sec. Power values corresponding to CHF for these conditions varies between 1.05 to 7.33 MW. Uniform and cosine shaped axial power profiles are considered in different tests. Radial power profiles A and B referred to in the later sections are shown here in Fig. 2.

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	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

Type B

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

Fig. 2: Radial power profile A and B

2.1 Steady State CHF Predictions

Assembly A0 (5x5 matrix, 25 heated rods, 5/2/6 Mixing Vane (MV)/Non-Mixing Vane (NMV)/Simple Spacers (SS) with radial power profile A and uniform axial power profile) was simulated first with the START code. The results are shown in Fig. 3. Simulated results are mostly within ±10% range of experimental values. Similar to results present in literature [4], [5], simulations tend to over-predict the CHF value for A0 configuration. A mean value of 0.35 and standard deviation value of 0.14 is obtained from the test results.

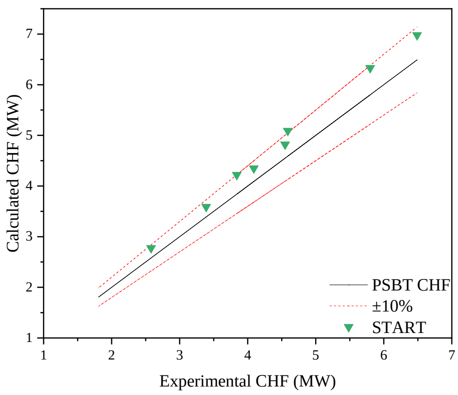

Fig. 3: CHF prediction for A0 configuration using START

Assembly A2 is similar to assembly A0 but differs in number/position of grid spacers. A2 has 7/2/8 MV/NMV/SS in a 5x5 matrix with radial power profile A and uniform axial power profile. Results obtained are shown in Fig. 4. A2 results are within acceptable range with slight under-prediction as compared to experimental results. Similar trend has been reported by other studies [4, 5] . Mean and standard deviation values for A2 assembly are -0.26 and 0.15 respectively.

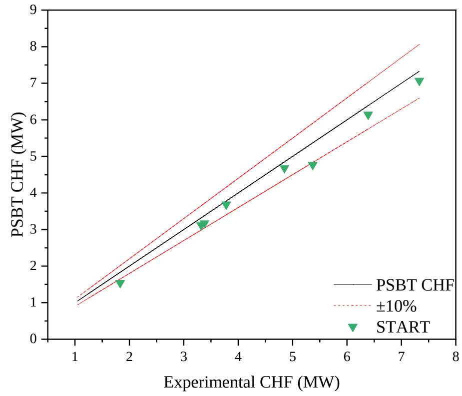

Fig. 4: CHF prediction for A2 configuration using START

A4 and A13 uses the same geometrical setup i.e. 5x5 matrix with 25 heated rods and 7/2/8 MV/NMV/SS along with radial power profile A. A4 and A13 both uses cosine shaped axial power profile. The results for both these assemblies are shown in Fig. 5.

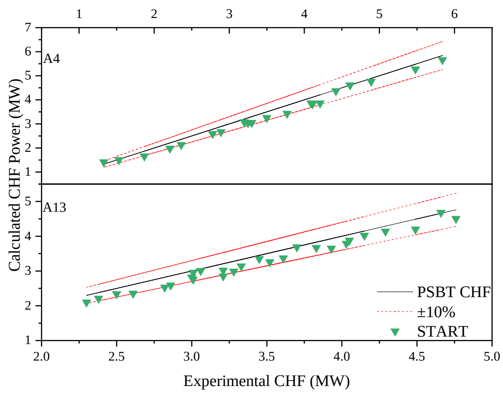

Fig. 5: CHF prediction for A4 and A13 using START

A8 configuration is similar to A4 and A13 configurations with the differences being radial power profile shape is B and 5x5 matrix contains 24 heated rods with central rod being a thimble rod (unheated rod). The results obtained for this configuration are shown in Fig. 6.

Mean values for A4, A8 and A13 test matrix are -0.18, -0.04 and -0.19 respectively. Standard deviation for these configurations are 0.11, 0.17 and 0.09. Overall trend is similar to previous reported studies. It is believed that future inclusion of axial flux distribution correction factor (K5) can help improve results further.

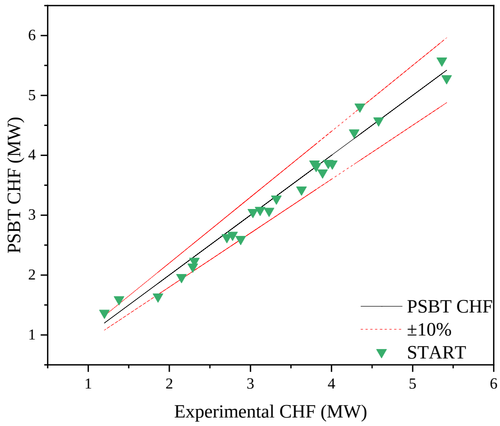

Fig. 6: CHF prediction for A8 using START

2.2 Transient CHF Predictions

Using the same configuration as A4 and A8, presented earlier, transient tests are carried out. These tests are labeled as 11T and 12T respectively. Four different transient scenarios are simulated using each assembly. These are power increase (PI), flow reduction (FR), depressurization (DP) and Inlet Temperature Increase (TI). Predicted value of time at which CHF would occur is plotted along with experimental conditions for both 11T and 12T tests for each kind of scenario. Figs. 7, 8, 9 and 10 show results for PI, FR, DP and TI scenarios, respectively.

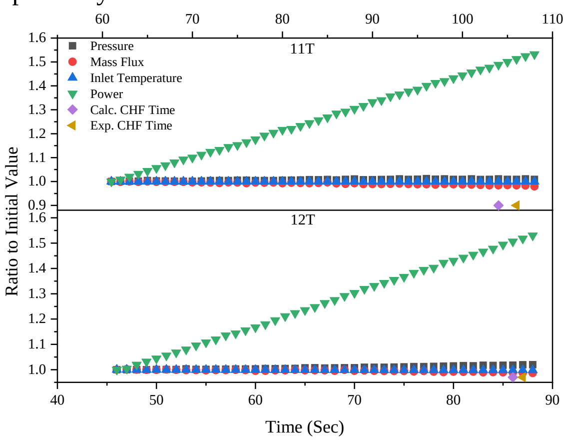

Fig. 7: Experimental conditions and CHF occurrence time for power increase scenario

Predicted Value of CHF power and time of CHF occurrence is compared with experimental values. The results are presented in Fig. 11 (CHF power) and Fig. 12 (CHF occurrence time).

Results indicate that START predictions are well compared with experimental values. The differences are reasonable and except for depressurization case in 12T configuration, predicted results are on conservative side. Similar to steady state results, it can be expected that results will improve to some extent with inclusion of correction factor for axial flux distribution (K5).

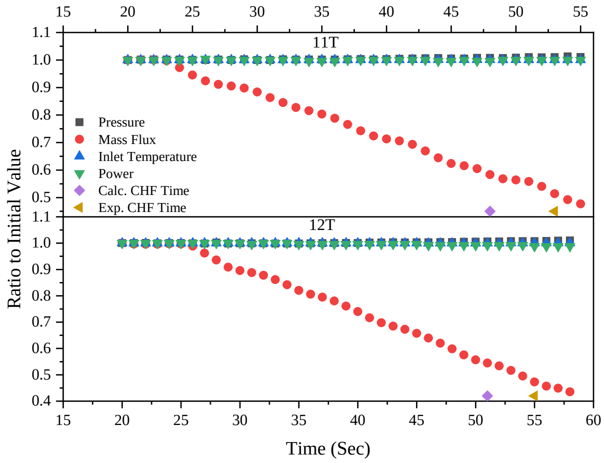

Fig. 8: Experimental conditions and CHF occurrence time for flow reduction scenario

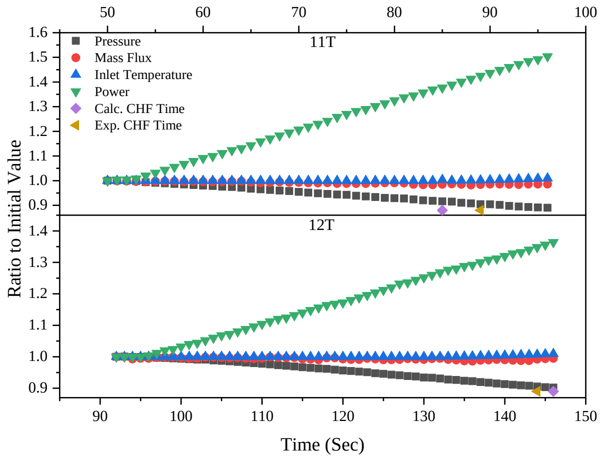

Fig. 9: Experimental conditions and CHF occurrence time for depressurization scenario

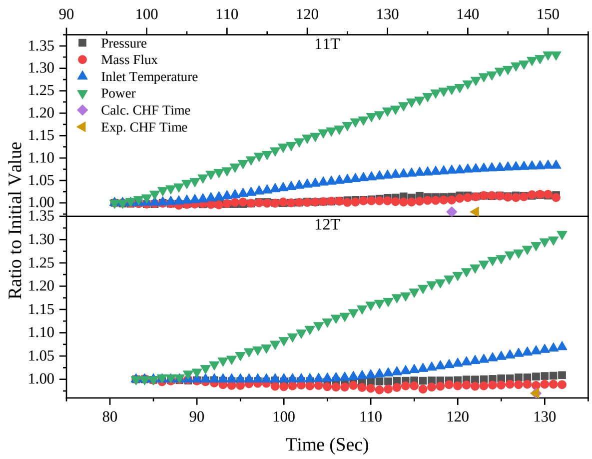

Fig. 10: Experimental conditions and CHF occurrence time for inlet temperature increase scenario

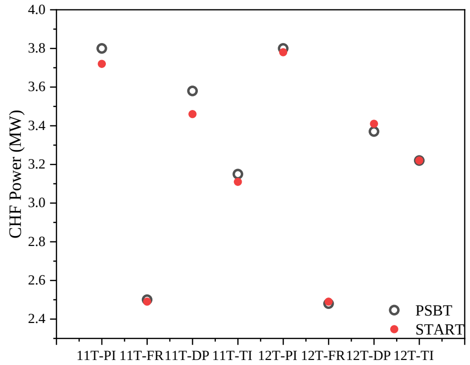

Fig. 11: CHF power comparison of START for time dependent PSBT cases

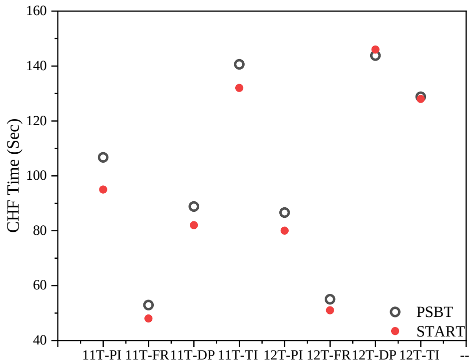

Fig. 12: CHF occurrence time comparison of START for time dependent PSBT cases

3. Conclusions

Sub-channel thermal-hydraulic simulations have been carried out to validate the CHF prediction capability of START code. 2006 Groeneveld CHF LUT with relevant correction factors have been implemented in the code. Generally a reasonable agreement is seen between simulations and experimental results, considering general limitation of homogenous model on which the START code is based. Comparison of CHF power and CHF occurrence times for transient cases shows acceptable agreement with experiment. Except for depressurization transient (12T-DP), CHF predicted power and time of occurrence are on conservative side.

ACKNOWLEDGMENTS

This work was supported by the National Research Foundation of Korea (NRF) Grant funded by the Korean Government (MSIP) (NRF-2016R1A5A1013919).

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