ANALYSIS OF INSCSP-R7 STANDARD PROBLEM IN ENTEK BM TEST FACILITY USING ANSYS CFX CODE WITH CALIBRATION OF PARAMETER IN BOILING MODEL

HOANG TAN HUNG, BUI THI HOA, HOANG MINH GIANG

Institute for Nuclear Science and Technology

Email: hoangtanhung1991@gmail.com

Abstract: INSCSP-R7 Standard Problem based on ENTEK BM Test Facility is investigated by RELAP5 code for prediction of averaged cross-section void fraction in vertical boiling channel of 7 m height. This standard problem also gives a challenge in application of CFD code such as ANSYS CFX to predict void fraction along the channel mentioned above due to: (a) only ten measured averaged cross-section void fraction given along the channel of 7 meters and (b) CFD simulation of boiling flow is mainly appropriate with sub cooled boiling. This study presents prediction of averaged cross-section void fraction along the channel of INSCSP-R7 Standard Problem using ANSYS CFX with calibration of parameter in boiling model based on experiment measured results.

Keyword: *Boiling Flow, Boiling Flow, ENTEK BM, CFD, ANSYS CFX, RELAP5*

I. Introduction

INSCSP-R7 Standard Problem based on ENTEK BM Test Facility is presented in the Ref.[1] together with results from using 1D code RELAP5/MOD3.2 for calculating averaged cross-section void fraction. As reported in the Ref [1], the calculated void fraction follow the same trend with axial position as the experiment results. Most (i.e., 70%) of the calculated values are within the ±0.03 experiment error margin of the experiment results. In the Ref[2] the void fraction prediction by CTF code is also investigated with some conclusion: (a) CTF boiling model tend to under predict void fraction in sub cooled region where void fraction below 0.2 and tend to over predict void fraction at nucleate boiling region where void fraction above 0.2 and (b) CTF give void fraction distribution predictions for most all base cases are good agreement with experiment distributions with mainly deviation within experiment measured accuracy for void fraction (0.03 of void) and the maximum deviations with 0.1 of void between CTF prediction and experiment occur at downstream of channel in some tests. In this study the ANSYS CFX code is used to simulation of boiling channel of INSCSP-R7 Standard Problem with physical models such as (a) sub cooled boiling at a heated wall and (b) modeling of the momentum transfer similar as presented in the Ref [3]. As known ANSYS CFX belong to class of CFD codes and their application of boiling channel simulation still encounters a lot of challenges due to requirement in appropriate employment from various sub models. For example, with regard to sub cooled boiling at a heated wall It can be found many sub models related to RPI wall boiling model such as nucleation site density, bubble departure diameter, bubble departure frequency which are introduced in the Ref. [4] and [5]. It is also observed that no universal setting up of boiling model for a series of test cases in specific experiment. That is why calibrations of several parameters for simulation specific test case are presented in the Ref. [6] and [7]. Thus, with this report, by investigation of INSCSP-R7 Standard Problem based on ENTEK BM Test Facility, two following studied issues are presented, that include (a) calibration of bubble departure diameter and mean bubble diameter in the bulk of water related to evaporation and condensation models are carried out under guide of measured experiment data and (b) furthermore calibration of two above parameters in general case without guide from measured experiment data.

II. Simulation boiling channel of ENTEK BM Test Facility

ENTEK BM facility

As mentioned in [1], Figure 1 provides a vertical and cross-section view of the test section which is also called as Heated Release Zone (HRZ). For the cross section view, the diameters are shown in millimeters. The HRZ contains a 7-rod bundle made by stainless steel (X18H10T). All the rods are hollow with outer diameter of 13.5 mm, 1.25 mm wall thickness, and 7 m length. The bundle is contained within a stainless steel pressure tube (80 mm outer diameter and 5 mm wall thickness) with inner diameter of 49 mm and 10.5 mm wall thickness. The coolant flow area is 8.84×10-4m2 and the hydraulic diameter is 7.84 mm. There are 20 honeycomb-type pin spacing grids along the length of the

HRZ, starting 30 mm from the beginning of the HRZ and repeated every 350 mm. Thus, these spacing grids are similar to the spacers in the RBMK-1000 with a hydraulic loss coefficient of 0.4 based on measurements.

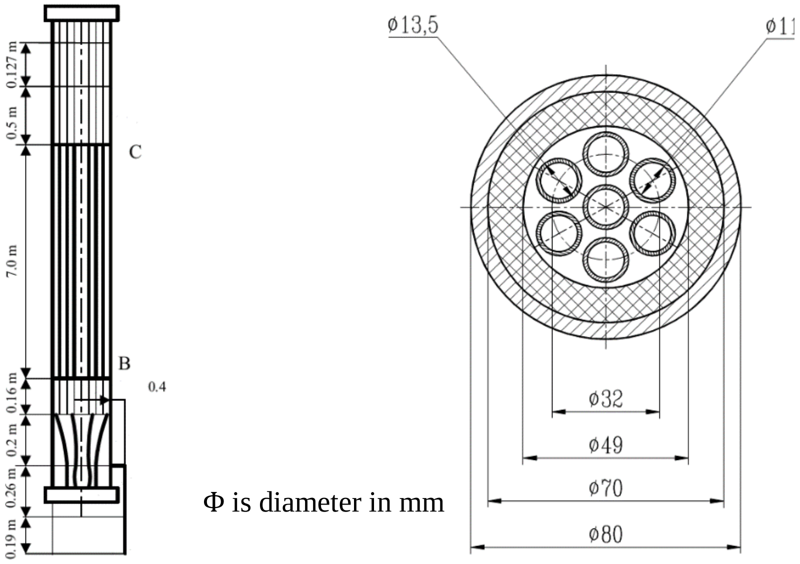


Figure 1 Test Section (Heat Release Zone) with vertical and cross section view [1]

The uncertainties of the measurements for each parameter are following for all tests are given in Table1:

Table1. Uncertainty of input parameters

Parameters	Uncertainty
Pressure at HRZ outlet	±1.5 %
Coolant mass flow rate	±0.0018 kg/s
Coolant temperature at HRZ inlet	±1 K
Electrical power	±2 kW
Void fraction	0.03; (void is calculated rather than measured

Mesh study

Due to symmetry of Heat Release Zone geometry, only one sixth of the channel is selected to simulate the boiling channel as illustrated in Figure 2.

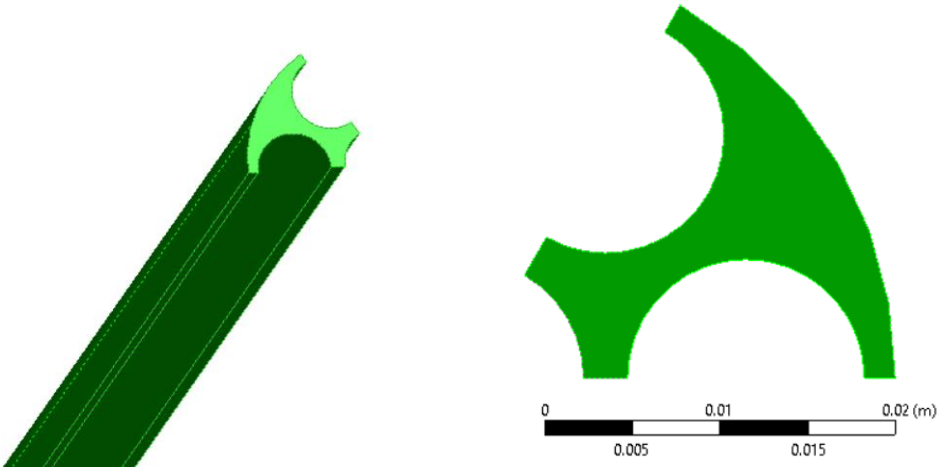
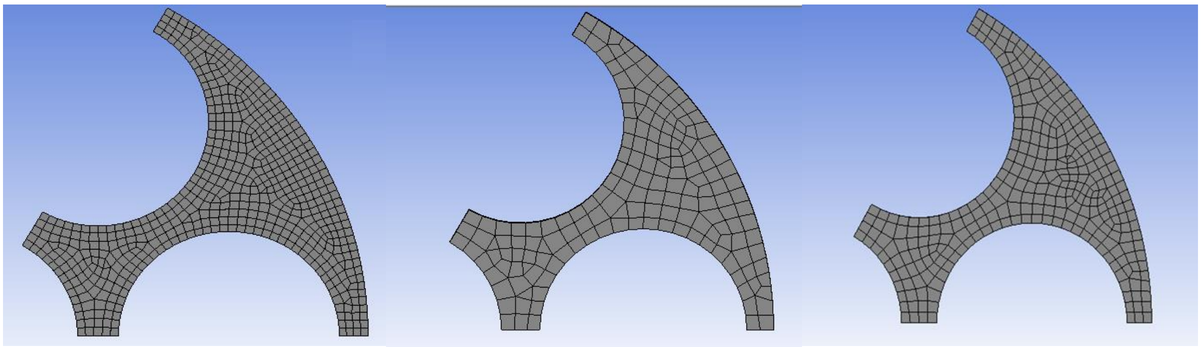


Figure 2 One sixth of the Heat Release Zone geometry selected in simulation

Several meshes are studied with geometry as illustrated in Figure 3 and mesh statistics as following. The element size (face) of corresponding Mesh 1, Mesh 2 and Mesh 3 are 5.e-004 m, 9.5e-004 m and

7.e-004 m. The axial number of division is 300, 350 and 200 accordingly and the total numbers of elements for each mesh are 169500, 60550 and 61800 accordingly.



Mesh 1 Mesh 2 Mesh 3

Figure 3 Three meshes used to study

Due to only averaged void fraction in the channel is interested so that, in that terms, averaged void fraction calculated by these three meshes give the similar results. For example, Figure 4 shows the calculated averaged cross-section void fraction for test case T04. Thus, for further study, Mesh 2 is selected in order to reduce calculation time.

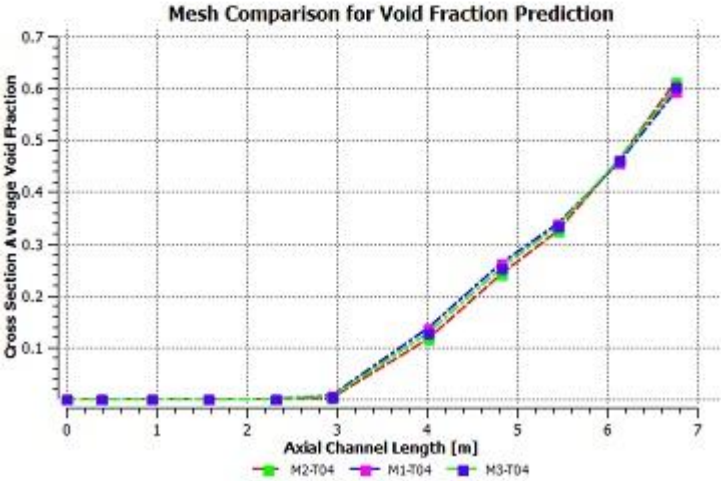


Figure 4 Mesh comparisons for calculated averaged cross-section void fraction

III. Sensitivity study on bubble size for Bubble Departure Diameter and Mean Bubble Diameter

The Bubble Departure Diameter (bubble size at detachment) is key parameter of evaporation rate in RPI wall boiling model that is employed in most of CFD boiling model. The evaporation rate is given by:

$$\dot{m}_{\beta\alpha} = \frac{Q_e}{(h_{g,sat}-h_l)} = \frac{\pi}{6} d_w^3 \rho_g f n \qquad (1)$$

The model of the bubble size at detachment given by Tolubinsky and Kostanchuk (1970) for water at different pressures and sub cooling is expressed as following:

$$. \mathrm{d_w} = \min\left(\mathrm{d_{ref}} \exp\left(-\frac{\Delta \mathrm{T_{sub}}}{\Delta \mathrm{T_{ref}}}\right),\ \mathrm{d_{max}}\right) \qquad (2)$$

For the high pressure of water the parameters $\mathrm{d_{ref}}$, $\Delta\mathrm{T_{ref}}$ and $\mathrm{d_{max}}$ is selected as 0.6mm, 45K and 1.4 mm correspondingly. The Mean Bubble Diameter d_β is also key parameter related to condensation model. In the CFX, vapor is always assumed in saturated condition. So that in a bulk of liquid heat is only transferred from vapor to liquid. The heat transfer per volumetric unit, Q_l, is defined as below.

$$Q_l = h_{lg} A_{lg} (T_{sat} - T_l) \tag{3}$$

Where the interfacial area density A_{lg} is given by $A_{lg} = \frac{6r_g}{d_\beta}$ and the heat transfer coefficient from vapor to liquid h_{lg} is estimated by Nusselt number $h_{lg} = \frac{\lambda_l Nu_{lg}}{d_\beta}$. Thus, Mean Bubble Diameter is inversely proportional with heat transfer coefficient from dispersed phase to continuous phase.

To close the phase transition model in the bulk bubbly flow with a mean bubble diameter d_β, Kurul and Podowski (1991) and also proposed to calculate the bubble diameter d_β locally as a linear function of liquid sub cooling T_{sub}:

$$d_\beta = \frac{d_{b1}(T_{sub} - T_{sub,2}) + d_{b2}(T_{sub,1} - T_{sub})}{(T_{sub,1} - T_{sub,2})} \tag{4}$$

In which d_{b1} = 0.1mm at $T_{sub,1}$ = 13.5K and d_{b2} =2mm at $T_{sub,2}$ = -5K.

The Nusselt number can be chosen from several correlations such as Ranz Marshall Model:

$$Nu_{lg} = 2 + 0.6 Re^{0.5} Pr^{0.3} \tag{5}$$

In the Ref. [6] and [7] the calibration of bubble size for both Bubble Departure Diameter and Mean Bubble Diameter are performed in order to get appropriate calculation results when simulation DEBORA experiment. The RPI wall boing model can be expressed as following:

$$q''_w = A_1 h_c (T_w - T_l) + A_2 h_q (T_w - T_l) + A_2 \frac{\pi}{6} d_w^3 \rho_g f n \tag{6}$$

If giving sensitivity to Bubble Departure Diameter by multiply factor S to d_{ref} then it is got repartitioning heat flux to the convection, quenching and evaporation portions with increase or decrease of evaporation portion.

$$q''_w = A_1 h_c (T_w - T_l) + A_2 h_q (T_w - T_l) + S * A_2 \frac{\pi}{6} d_w^3 \rho_g f n \tag{7}$$

Sensitivity on Bubble Departure Diameter

The Figure 5 shows the calculated averaged cross-section void fraction along the channel based on different Bubble Departure Diameters. The different value of S were investigated such as 1.0 (default), 0.5 and 0.08.

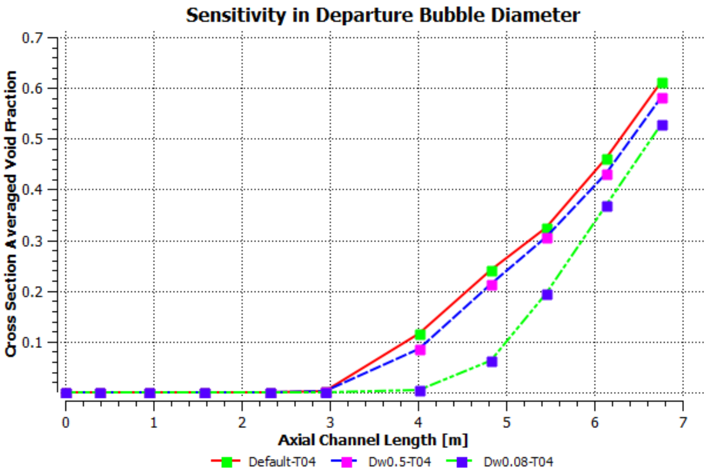


Figure 5 Averaged cross-section void fractions with different Bubble Departure Diameters

It is observed that void with S =1 is highest and void with S=0.08 is lowest. In the case S=0.08 the void fraction at the upstream is lower significantly in comparison with default case. In general, the smaller S then the smaller voids fraction archived.

Sensitivity on Mean Bubble Diameter

The Figure 6 shows the calculated averaged cross-section void fraction along the channel based on different Mean Bubble Diameters. The different value of S multiplied with d_β in equation (4) were investigated such as 1.0 (default), 5, 15 and 17. In general, the larger S then the smaller voids fraction archived. The significant different void fraction occurs at the downstream where the boiling regime is most saturated boing in INSCSP-R7 Standard Problem.

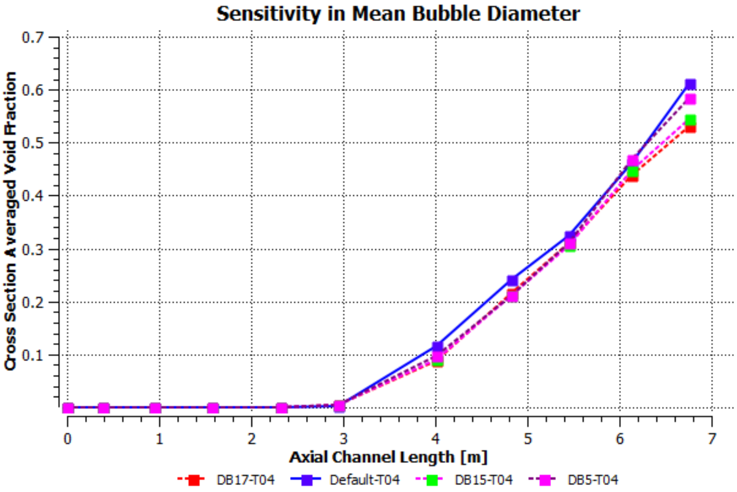


Figure 6 Averaged cross-section void fractions with different Mean Bubble Diameter

Thus, it is found that by variants of different value of factor S used to multiply to $\mathrm{d_{ref}}$ and d_β then the curve of averaged cross-section void fraction along the heated channel can be controlled to be smaller or lager based on value of factor S.

IV. Parameter calibration for averaged cross-section void based on experiment measured data

Thus, it is found that by multiplication of different factor S to $\mathrm{d_{ref}}$ and d_β the sensitivity on Bubble Departure Diameter and Mean Bubble Diameter were investigated and calibration can be based on two this parameters to decrease or increase of averaged cross-section void fraction along the channel. The combination from increase of Mean Bubble Diameter and decrease of Bubble Departure Diameter will result to decrease of averaged cross-section void fraction along the channel.

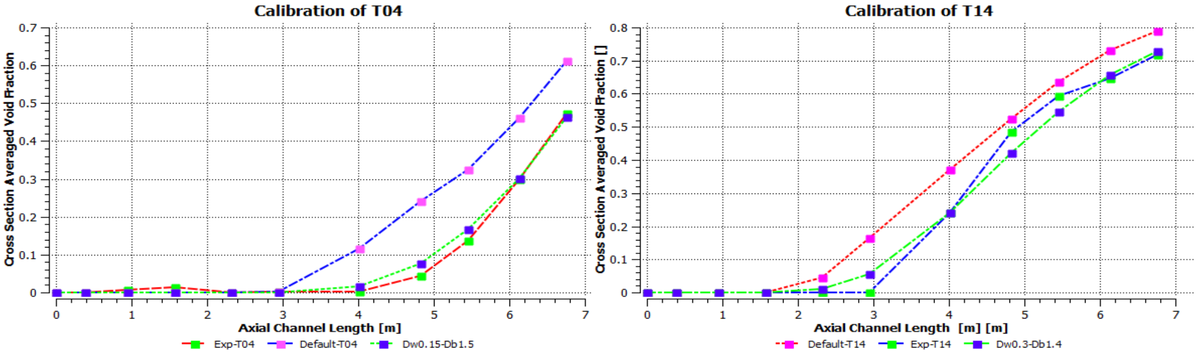


Figure 7 Averaged cross-section void fractions with calibrations $\mathrm{d_{ref}}$ and d_β for test cases 3MPa

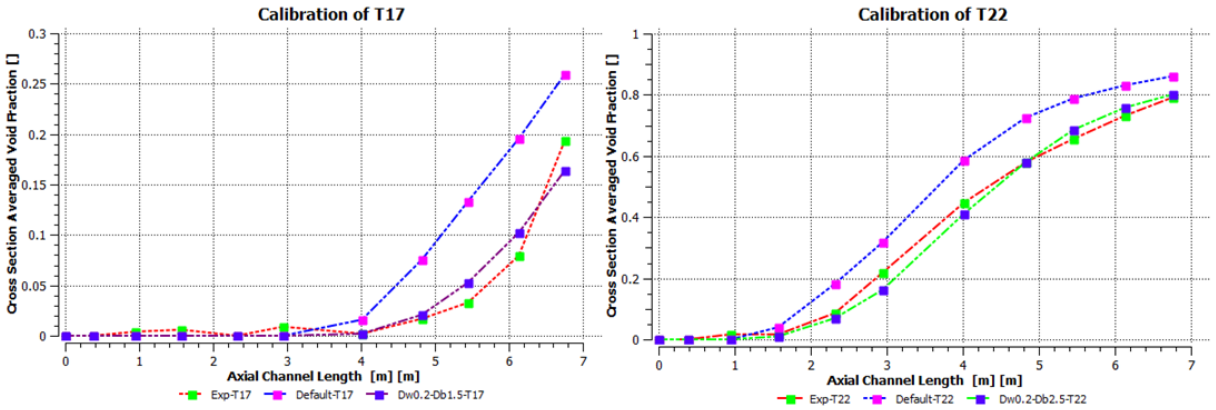


Figure 8 Averaged cross-section void fractions with calibrations $\mathrm{d_{ref}}$ and d_β for test cases 7MPa

Figures 7 and 8 show the curves of Averaged cross-section void fractions along the channel were calibrated by changing $\mathrm{d_{ref}}$ and d_β using multiplication factor S. As shown in Figure 7 the test case T04 was calibrated by multiplication of 0.15 for $\mathrm{d_{ref}}$ and of 15 for d_β. With regard to test case 14 the values of multiplication factor 0.3 and 1.4 were used to change $\mathrm{d_{ref}}$ and d_β. Figure 8 shows the values of multiplication factor of 0.2 for $\mathrm{d_{ref}}$ and 1.5 for d_β in order to calibrate test case T17 and of 0.2 for $\mathrm{d_{ref}}$ and 2.5 for d_β in order to calibrate test case T22. Table 1 shows the calibrated Departure Diameter and Mean Bubble Diameter for several test cases with different input parameters including pressure in two ranges: 3MPa and 7MPa. As shown in the Ref. [6] and Ref.[7] parameter calibration is applied only for specific individual test case and it is observed from Table 1 that it could hardly derive a correlation or a mapping between four input parameters (pressure, mass flow rate, heated power and inlet temperature) and the Departure Diameter or Mean Bubble Diameter. So that even based in a given database such as Table 1 it is very difficult to have a general method to estimate d_{ref} and d_β. Up to now it can be concluded that parameter calibrations mostly bases on experiment data only.

Table 1. Calibrated Departure Diameter and Mean Bubble Diameter for several test cases

Test Case	Pressure (MPa)	Mass flow rate (kg/s)	Heated power (kW)	Inlet Temperature (K)	d_{ref}	d_β
04	3.11	0.8816	297.6	451	0.15	1.5
05	3.1	0.8662	295	484	0.5	10.0
12	3.11	1.3301	504.3	449	0.25	1.5
14	3.11	1.7644	511.3	476	0.3	1.4
17	7.17	0.8821	302.8	496	0.2	1.5
22	7.32	0.8825	513.4	514	0.2	2.5
23	7.16	1.3243	515.8	485	0.17	2.5
25	7.16	0.8849	632.1	454	0.25	1.5

V. Parameter calibration for averaged cross-section void based on CTF calculation

As mention in previous paragraph, based on a specific four input parameters including pressure, mass flow rate, heated power and inlet temperature, it could hardly introduce an appropriate d_{ref} and d_β without experiment data. Then, it is introduced here the results from CTF calculation instead of experiment data to be used for parameter calibration in evaporation and condensation models in ANSYS CFX. In this study, INSCSP-R7 Standard Problem based on ENTEK BM Test Facility is also investigated by CTF code and the results of averaged cross section void fraction given by CTF will take role instead of experiment data. As known, CTF is verified and validated code that is widely used in thermal hydraulic analysis in nuclear reactor so that calculation results from this code such as average cross section void fraction is highly recommended to be used if have no experiment data.

When using CTF calculation of void fraction, in almost test cases, the saturated boiling occurs always at downstream where CFD codes including ANSYS CFX cannot give appropriate results of void fraction. This issue results from RPI wall boiling model developed mainly for sub cooled boing regime.

In CTF code, evaporation and condensation induced by thermal phase change. The heat from wall is assumed to transfer directly to fluid by following formula:

$$q_w''' = h_c(T_w - T_l)\frac{A_s}{A_x \Delta X} \tag{8}$$

Whenever heat from the wall is transferred to liquid, liquid enthalpy increases and the phase change which is expressed via volumetric mass flow rate, Γ''', is calculated by subtracting condensation terms (sub-cooled liquid and vapor terms) from evaporation terms (superheated liquid and vapor) terms:

$$\Gamma''' = \left[\frac{A'''_{int,shl}\ h_{i,shl}}{\left(h_{g,sat} - h_{l,sat}\right)C_{pl}}\left|h_l - h_{l,sat}\right| + \frac{A'''_{int,shv}h_{i,shv}}{\left(h_{g,sat} - h_{l,sat}\right)C_{pv}}\left|h_g - h_{g,sat}\right|\right]$$

$$-\left[\frac{A'''_{int,scl}h_{i,scl}}{\left(h_{g,sat} - h_{l,sat}\right)C_{pl}}\left|h_l - h_{l,sat}\right| + \frac{A'''_{int,scv}h_{i,scv}}{\left(h_{g,sat} - h_{l,sat}\right)C_{pv}}\left|h_g - h_{g,sat}\right|\right] \tag{9}$$

Thus, for the region of saturated boiling CTF will give liquid temperature at saturation condition. This issue differs from CFD code due to RPI wall boing model allow quenching portion which can results to give liquid temperature higher than saturation condition. Otherwise, ANSYS CFX can give more appropriate results of void fraction in sub cooled region due to advantage of RPI wall boing model. Thus, it can drive a method of parameter calibration for general case as following:

(a) Use CTF to predict void fraction of test case. Then it can determined the segment of sub cooled boiling based on output from CTF results
(b) Partition whole heated channel into 2 parts: the first is sub cooled and the second is saturated regions.
(c) Simulation of whole heated channel with notice that at the parameter calibration is applied only at saturated region but not in sun cooled one.

Following the above method, it could be used both the advantages from CFD and CTF codes. For the upstream segment of heated channel when sub cooled boiling occurs the ANSYS CFX can simulate this phenomena based on local parameters such as d_{ref} and d_β while CTF code with unique boiling model as mention in formula (9) cannot simulate it appropriately. At the downstream where saturated boiling occurs ANSYS CFX code cannot give appropriate results of averaged cross void fraction rather than CTF code then the parameter calibration is implemented based on CTF results. Even d_{ref} and d_β are local parameter but the calibration of them in fact is repartitioning heat transferred from wall to water as mention in the formulas (6) and (7). Of course changing these local parameters may affect to other local phenomena such as momentum transfer but it is here interested only in averaged cross section void fraction so this method should be applicable.

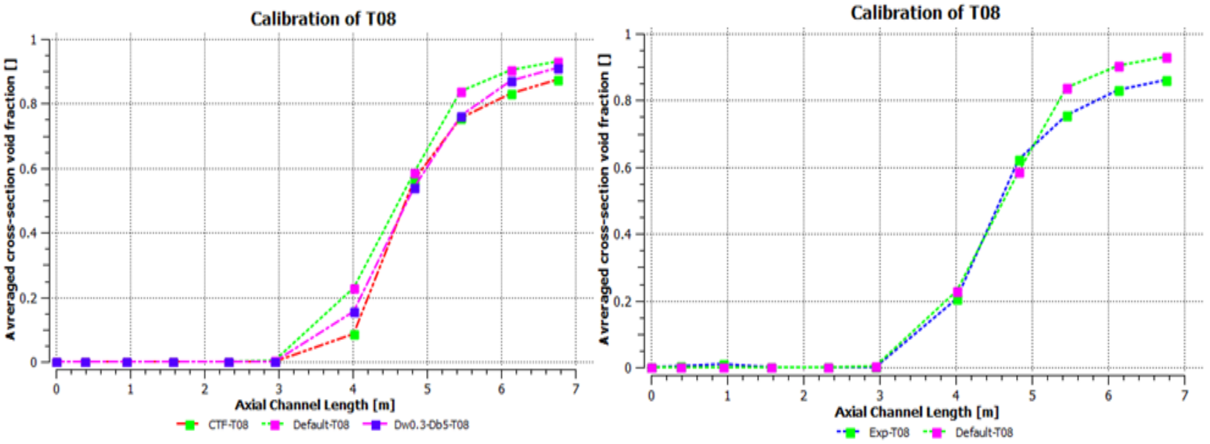


Figure 9 Averaged cross-section void fractions with calibrations based on CTF results for test case of 3 MPa and comparison with experiment measured data

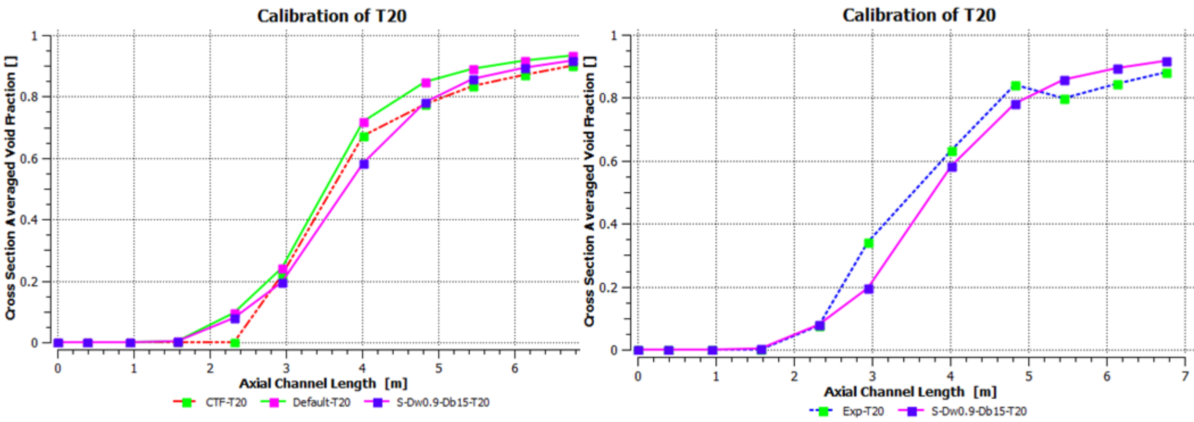


Figure 10 Averaged cross-section void fractions with calibrations based on CTF results for test case of 7 MPa and comparison with experiment measured data

Figures 9 and 10 show the averaged cross-section void fractions with calibrations based on CTF results for test cases T08 (with pressure of 3MPa) and T20 (with pressure of 7 MPa). In two Figures above the left show the curves of CTF void prediction, default ANSYS CFX void prediction and the ANSYS CFX calibrated void prediction. Otherwise, the right show the comparisons between ANSYS CFX calibrated void prediction and experiment measured data. It is seen that the resonable results achieved from this method of parameter calibration.

VI. Conclusions

As mention above ANSYS CFX used to simulate boiling channel still encounters a lot of challenges due to requirement in appropriate employment from various sub models. It is also observed that no universal setting up of boiling model for a series of test cases in specific experiment. That is why calibrations of several parameters for simulation specific test case are presented in several works. In this study, It is obseved that the sensitivity on Bubble Departure Diameter and Mean Bubble Diamter will affect much to void fraction prediction of the ANSYS CFX. Then by using multiplication factor to change these parameters it is driven to a method for parameter calibration of boiling and condensation models in ANSYS CFX. However, the parameter calibration is mainly based on experiment date and is applicale for a specific single tets case only. Thus, based on a specific four input parameters including pressure, mass flow rate, heated power and inlet temperature, it could hardly introduce an appropriate d_{ref} and d_{β} without experiment data. Then it is recommended to divide the heated channel in two segments: upstream and downstream based on using CTF caluculation. At the upstream where sub cooled boiling occurs the defaul model of ANSYS CFX can be applicale. At the downstream when saturated boiling occurs the parameter calibration is implemented based on CTF reslts will give more approprepriate results of avergaed cross section void fraction. Thus with assistance of CTF code for parameter calibration the results from ANSYS CFX void fraction prediction can be improved significanly.

Nomenclature

$\dot{m}_{\beta\alpha}$	Evaporation rate (kg/s)	T_w	Wall temperature (K)
A_1	Wall area fraction cover by water	A_s	Conductor surface area in mesh cell (m^2)
A_2	Wall area fraction cover by vapor bubbles	A_x	Mesh-cell area, X normal (m^2)
$A'''_{int,scl}$	Sub-cooled liquid interfacial area per unit volume (m^1)	Q_e	Evaporation heat flux (W /m 2)
$A'''_{int,scv}$	Sub-cooled vapor interfacial area per unit volume (m^1)	Q_l	Liquid heat flux (W /m 2)
$A'''_{int,shl}$	Super-heated liquid interfacial area per unit volume (m^{-1})	T_{sat}	Saturate temperature (K)
$A'''_{int,shv}$	Super-heated vapor interfacial area per unit volume (m^{-1})	d_w	Bubble departure diameter (mm)
h_c	Convection heat transfer coefficient (W/m^2.K)	d_{β}	Mean bubble diameter (mm)
$h_{int,scl}$	Sub-cooled liquid interface heat transfer coefficient (W/m2.K)	ρ_g	Gas density (kg/m^3)
$h_{int,scv}$	Sub-cooled vapor interface heat transfer coefficient (W/m2.K)	C_{pl}	Liquid specific heat, constant pressure (J/kg.K)

$h_{int,shl}$	Super-heated liquid interface heat transfer coefficient (W/m2.K)	C_{pv}	Vapor specific heat, constant pressure (J/kg.K)
$h_{int,shv}$	Super-heated vapor interface heat transfer coefficient (W/m2.K)	S	Multiply factor
$h_{l,sat}$	Liquid saturation enthalpy (J/kg)	Nu	Nusselt number
h_q	Quenching heat transfer coefficient (W/m^2.K)	Pr	Prandtl number
$h_{g,sat}$	Vapor saturation enthalpy (J/kg)	Re	Reynolds number
h_l	Liquid enthalpy (J/kg)	f	Bubble Detachment Frequency (Hz)
T_l	Liquid temperature (K)	n	Wall Nucleation Site Density
T_{sub}	Near-wall liquid sub-cooling (K)		

References:

[1] P. L. Garner.,(2002) “RELAP5/MOD3.2 Analysis of INSC Standard Problem INSCSP-R7: Void Fraction Distribution over RBMK Fuel Channel Height for Experiments Performed in the ENTEK BM Test Facility”, United States International Nuclear Safety Center, Reactor Analysis and Engineering Division, Argonne National Laboratory, April 2002.

[2] Hoang Minh Giang, Hoang Tan Hung, Nguyen Phu Khanh., (2015) “Investigation of CTF void fraction prediction by ENTEK BM experiment data”, Nuclear Science and Technology (ISSN 1810-5408), Vol5, No1, 2015 PP.8 -17.

[3] Eckhard Krepper, Bostjan Koncar ˇ, Yury Egorov, (2006) “CFD modelling of subcooled boiling—Concept, validation and application to fuel assembly design”, Nuclear Engineering and Design 237 (2007) 716–731.

[4] S.C.P. Cheung, S. Vahaji , G.H. Yeoh , J.Y. Tu (2014) Modeling sub cooled flow boiling in vertical channels at low pressures – Part 1: Assessment of empirical correlations. Article in press, International Journal of Heat and Mass Transfer xxx (2014) xxx–xxx.

[5] S.C.P. Cheung, S. Vahaji , G.H. Yeoh , J.Y. Tu, (2014) Modeling sub cooled flow boiling in vertical channels at low pressures – Part 2: Evaluation of mechanistic approach. Article in press, International Journal of Heat and Mass Transfer xxx (2014) xxx–xxx

[6] Eckhard Krepper, Roland Rzehak, (2016) “CFD for subcooled flow boiling: Simulation of DEBORA experiments”, Nuclear Engineering and Design 241 (2011) 3851–3866.

[7] E. Krepper, R. Rzehak, C. Lifante, Th. Frank, “CFD model of wall boiling considering the bubble size distribution”, NURETH15-333, The 15th International Topical Meeting on Nuclear Reactor Thermalhydraulics, NURETH-15 Pisa, Italy, May 12-15, 2013.

MÔ PHỎNG BÀI TOÁN CHUẨN INSCSP-R7 TRÊN THỰC NGHIỆM ENTEK BM DỰA TRÊN HIỆU CHỈNH THAM SỐ MÔ HÌNH SÔI BẰNG PHẦN MỀM ANSYS CFX

HOÀNG TÂN HƯNG, BÙI THỊ HOA, HOÀNG MINH GIANG

Viện Khoa học và Kỹ thuật Hạt nhân

Email: hoangtanhung1991@gmail.com

Tóm tắt: Bài toán chuẩn INSCSP-R7 dựa trên hệ thực nghiệm ENTEK BM về dòng sôi trong kênh thẳng đứng chiều dài 7m đã được phân tích bằng phần mềm hệ thống RELAP5 cho việc dự đoán hệ số pha hơi trung bình dọc theo kênh dẫn. Việc sử dụng chương trình CFD như ANSYS CFX để dự đoán hệ số pha hơi dọc theo kênh nêu trên luôn gặp phải thách thức do hai yếu tố sau: (a) chiều dài kênh sôi lớn trong khi chỉ có mười điểm đo thực nghiệm và (b) bản thân các phần mềm CFD chỉ mô phỏng phù hợp với trạng thái sôi dưới bão hòa (subcooled boiling). Báo cáo trình bày việc mô phỏng và dự đoán hệ số pha hơi trung bình dọc theo kênh bài toán INSCSP-R7 bằng phần mềm ANSYS CFX trên cơ sở hiệu chỉnh các tham số mô hình sôi sao cho phù hợp với dữ liệu thực nghiệm.

Từ khóa: *Dòng sôi, ENTEK BM, CFD, ANSYS CFX, RELAP5*