Korean Nuclear Society Spring Meeting, Yeosu, Korea,
24-26 Oct. 2018

Improvement of the Subcooled Boiling Model in MARS

for Low-Pressure, Low-Pe Flow Conditions

Tae Wook Ha, Byong Jo Yun, Jae Jun Jeong*
School of mechanical Engineering, Pusan National University, South Korea
jjjeong@pusan.ac.kr*

26. Oct. 2018

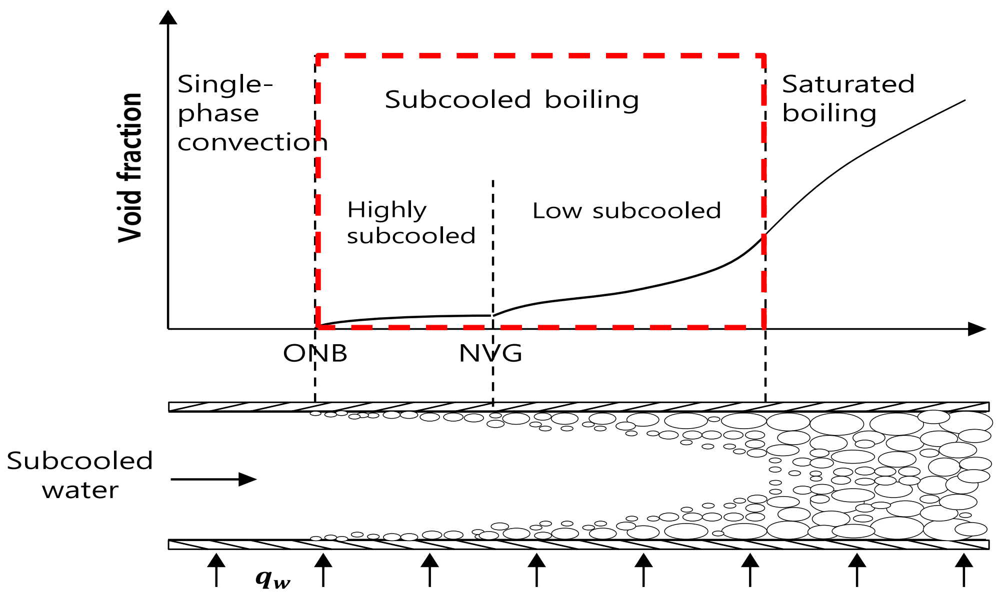
Contents

Contents

I. Introduction [1/2]

◆ The subcooled boiling

- Onset of Nucleate Boiling (ONB)
  - by Rousenow, 1964; Davis and Anderson, 1966., etc.
- The point of Net Vapor Generation **(PNVG)**
  - by Levy, 1966; Staub, 1968; **Saha-Zuber, 1974**



<Axial void fraction in subcooled boiling>
(Ha et al., ANE.2018)

I. Introduction [2/2]

◆ The subcooled boiling in MARS

- Consists of PNVG, wall evaporation, interfacial condensation, etc.
- Use "Savannah River Laboratory **(SRL) model**" as a default model
  - Consists of **PNVG** and **wall evaporation** models (Thurston, 1992)

<The package of SRL model >

SRL model	Pe($=GD_H c_{pf}/k_f$) ≤70,000	Pe>70,000
NVG	$Nu = \frac{q_w D_h}{k_f(T_{sat} - T_{NVGP})} = 455$ ※ Saha-Zuber model (1974)	$St = \frac{Nu}{RePr} = \frac{q_w}{Gc_{pf}(T_{sat} - T_{NVGP})}$ $= (0.0055 - 0.0009 \times F_{press})$ ※ Modified Saha-Zuber model (1974)
Wall evaporation	$\Gamma_w = \frac{q_w A_w}{V h_{fg}} \left(\frac{1}{1 + \frac{q_{pump}}{q_{evap}} F_{SRL}} \right) \left(M + F_{press}(\boldsymbol{F_{gam}} - M) \right)$ where, $Mul = \frac{h_l - h_{NVG}}{h_f - h_{NVG}}$, $F_{gam} = \min\begin{bmatrix} 1.0\ , 0.0022 + 0.11Mul - 0.59Mul^2 + 8.68Mul^3 \\ -11.29Mul^4 + 4.25Mul^5 \end{bmatrix}$. ※ Modified Lahey's model (1978)	

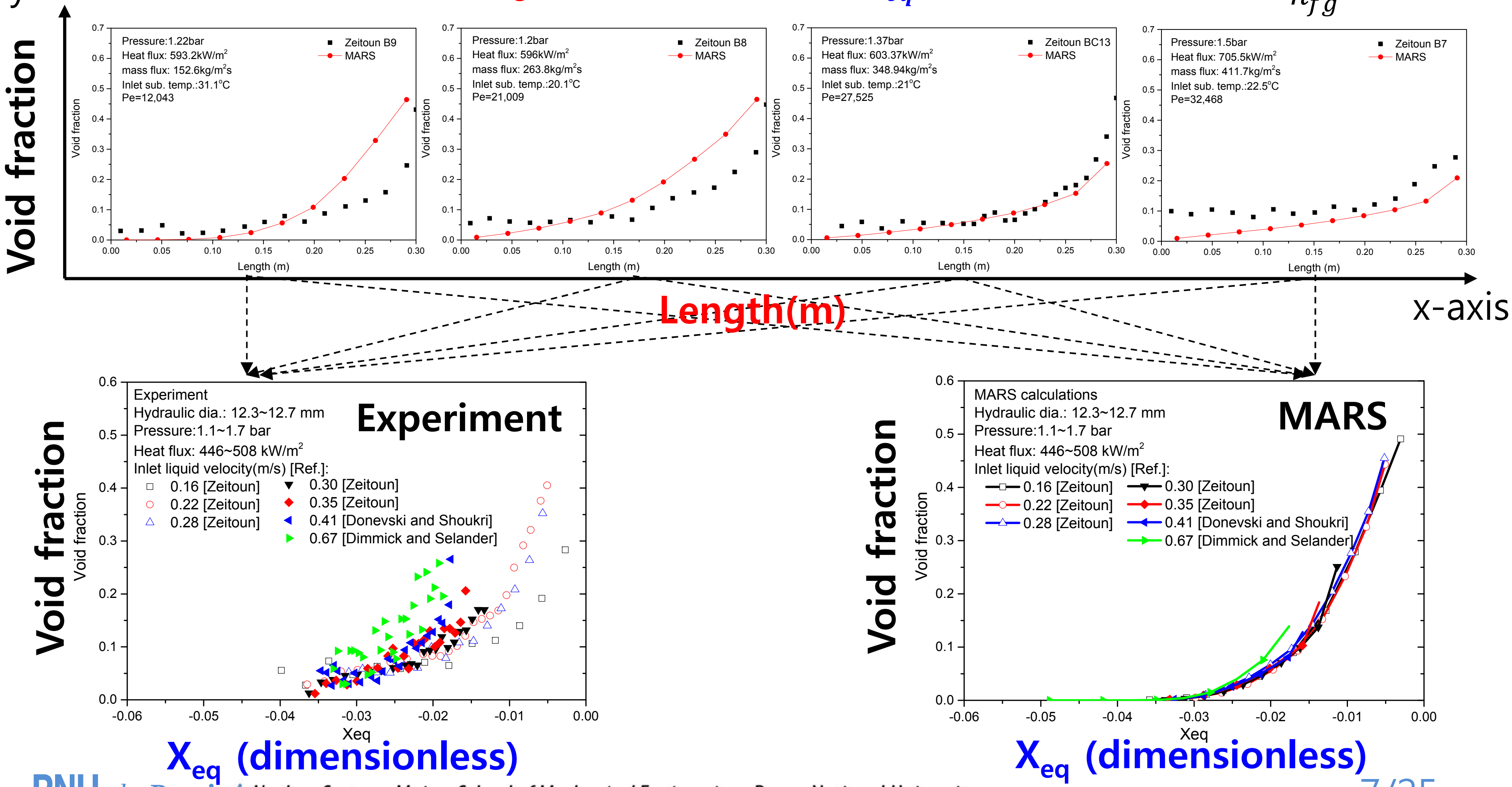
Contents

Ⅱ. Assessment of the SRL model [1/3]

◆ Deficiencies of the SRL model (1/3); Pe ≤ 70,000

- **Velocity effect**
  - Void fraction vs. Length → Void fraction vs. X_{eq}

$$X_{eq}(L) = \frac{\left(h_{in} + \frac{q_w P_h L}{\dot{m}}\right) - h_{f,sat}}{h_{fg}}$$

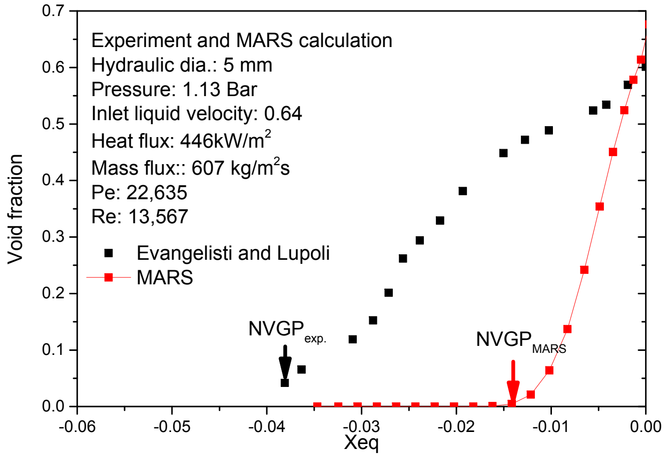


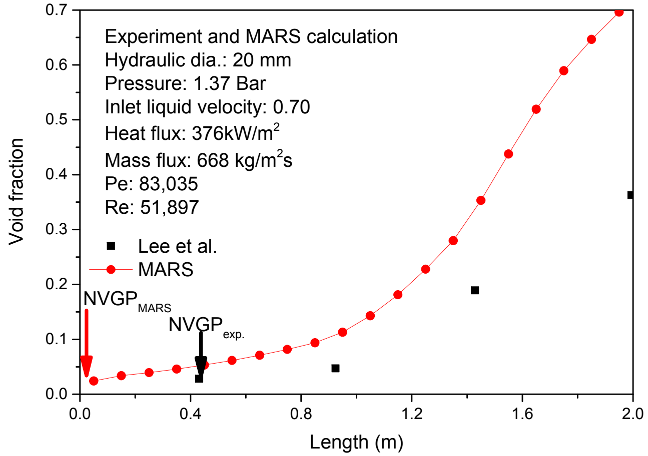
Ⅱ. Assessment of the SRL model [2/3]

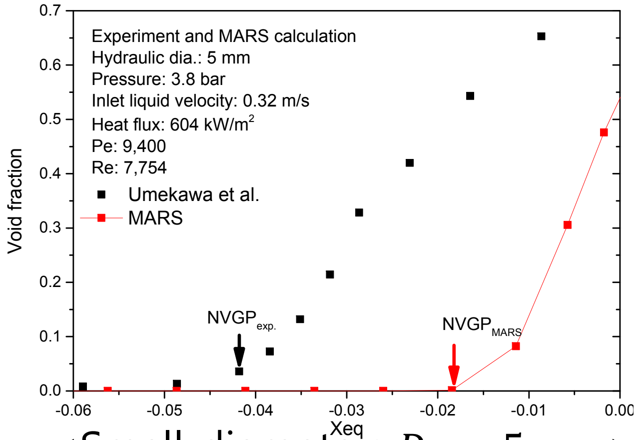
◆ Deficiencies of the SRL model (2/3);

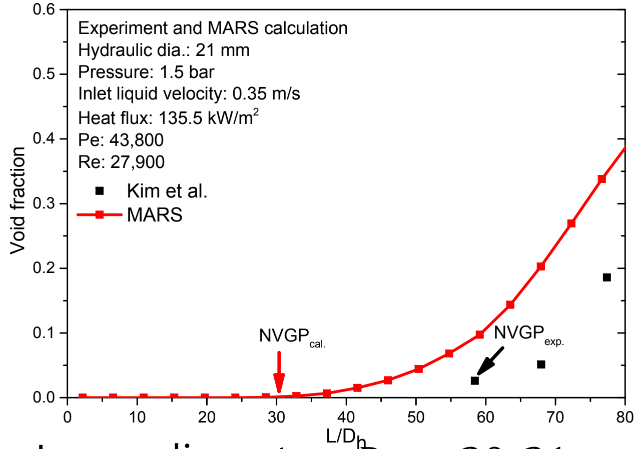
$$Nu = \frac{q_w \boldsymbol{D_h}}{k_f(T_{sat} - T_{NVGP})} = 455$$

- **Hydraulic dia. effect**









<Small diameter; $D_h = 5\ mm$>

<Large diameter; $D_h = 20, 21\ mm$>

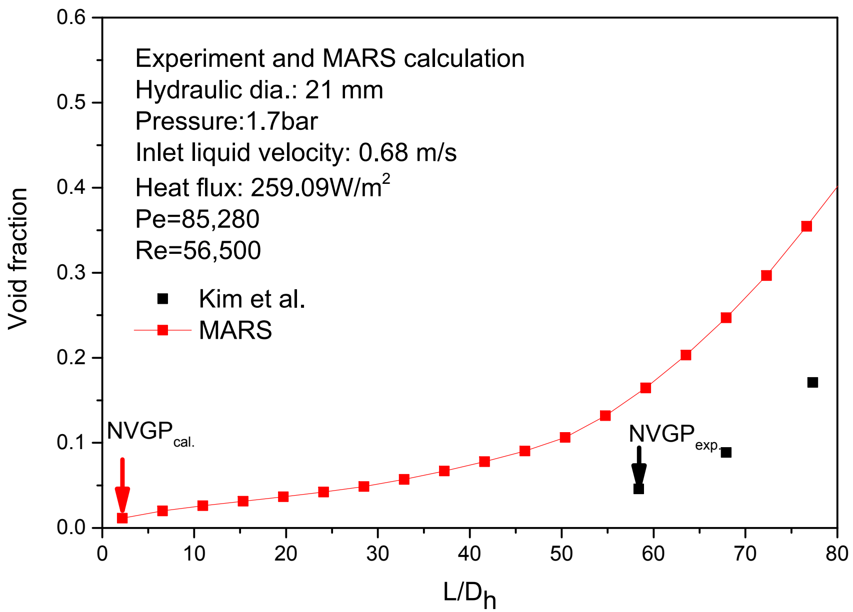
<Evangelisti and Lupoli, 1969; Umekawa et al., 2015>

<Lee et al., 2017; Kim et al., 2015>

Ⅱ. Assessment of the SRL model [3/3]

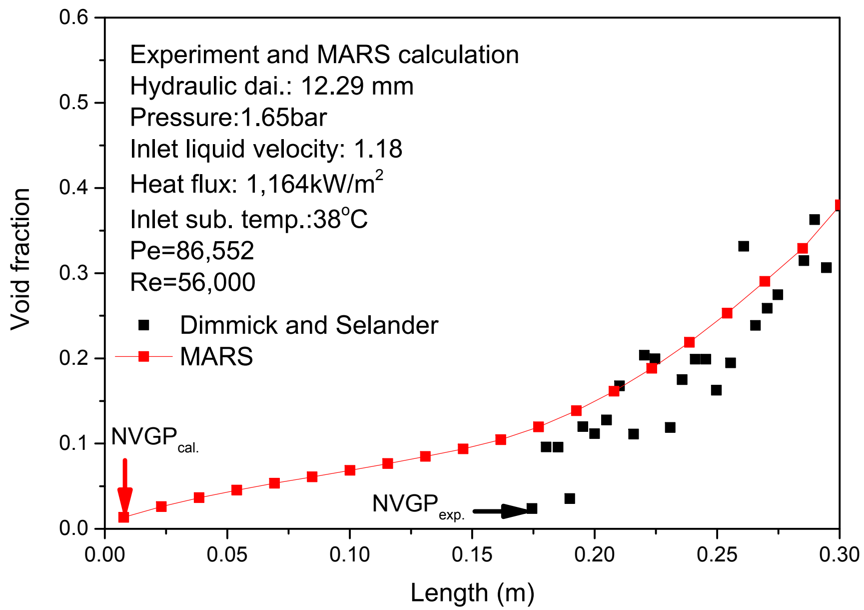
◆ Deficiencies of the SRL model (3/3)

- Criterion for NVGP model
  - **Pe=70,000?**
- Some authors have proposed criteria lower than 70,000
  - Kalitvianski, (2000), Ha et al. (2004), and Ha et al.(2018), etc.



<Pe=85,280>

<Kim et al., 2015>



<Pe=86,552>

<Dimmick and Selander, 1990>

Contents

Ⅲ. Proposal of improved S·B model [1/7]

◆ Collected the experimental data

- Covers applicable range of the SRL model*

Experiment	No. of tests	Press. (bar)	Heat flux (kW/m^2)	Mass flux ($kg/m^2 \cdot s$)	Pe	Geometry Type	D_h (mm)
Zeitoun	25	1.1~1.7	210~706	161~412	12,000~32,500	Annular	12.7
Mcleod	19	1.55	297~1186	65~480	3,600~26,600	Annular	8.9
Donevski and Shoukri	6	1.5~2.1	481~733	315~450	25,000~35,500	Annular	12.7
Dimmick and Selander	4	1.65	472~1164	620~1116	48,400~86,600	Tube	12.3
Evangelisti and Lupoli	3	1.2	446~885	607~1410	22,600~52,600	Annular	6
Kim et al.	4	1.3~1.7	97~259	334~653	44,000~86,000	Annular	21
Bibeau	6	1.55	300~980	67~252	3,800~14,200	Annular	9.1
Yun et al.	5	1.6~1.9	374~566	1104~2075	175,200~329,300	Annular	25.5
Lee et al.	2	1.1~1.5	375~377	668~684	83,000~85,000	Annular	20
Umekawa et al.	2	3.8~5.0	604~626	300	9,400~18,900	Tube	5,10
Ferrell and Bylund	6	4.1~8.2	246~530	440~542	33,600~41,000	Tube	11.9
Rouhani	18	9.8~50	300~902	79~533	8,100~45,200	Annular	13
Christensen	3	28~69	355~497	880~940	125,100~135,900	Rectangular	17.8
Total	**103**	1.1~69	97~1186	65 ~2075	3,600 ~329,300	-	5~25.5

*Applicable range of the SRL model: $1.01 \le P(bar) \le 138$, $5{,}000 \le Pe \le 345{,}000$, & $4.0 \le D_h \le$ **13** mm

Ⅲ. Proposal of improved S·B model [2/7]

◆ Proposal of a new NVGP model [1/4]

- Some authors assumed that
  - Single phase flow
  - Temperature distribution (radial)

  <Levy, 1967; Staub, 1968; Rogers et al., 1987>

- We assumed that
  - Related to the local Nussel number for laminar and turbulent flow of single phase

$$Nu = \frac{2}{\frac{11}{24} + \sum_{n=1}^{\infty} C_n exp\left(\frac{-\beta_n^2 x}{r_0} \frac{1}{Pe}\right) R_n(1)}$$ for laminar → $Nu = 455$ for Pe≤70,000

<Low velocity region>

<Siegel et al., 1958>

$$Nu = 0.0243 Re^{0.8} Pr^{0.4}$$ for turbulent → $St = (0.0055 - 0.0009 \times F_{press})$

<Dittus and Boelter, 1930>

$$St = \frac{Nu}{Re \cdot Pr}$$

for Pe>70,000

<High velocity region>

Ⅲ. Proposal of improved S·B model [3/7]

◆ Proposal of a new NVGP model [2/4]

- Some authors assumed that
  - Single phase flow
  - Temperature distribution (radial)

  <Levy, 1967; Staub, 1968; Rogers et al., 1987>

- We assumed that
  - Related to the local Nussel number for laminar and turbulent flow of single phase

$$Nu = \frac{2}{\frac{11}{24} + \sum_{n=1}^{\infty} C_n exp\left(\frac{-\beta_n^2 x}{r_0}\frac{1}{Pe}\right) R_n(1)}$$ for laminar ➡ $Nu = 455$ for Pe≤70,000

<Siegel et al., 1958>

$$Nu = 0.0243 Re^{0.8} Pr^{0.4}$$ for turbulent ➡ $$Nu = \left(0.0055 - 0.0009 \times F_{press}\right) Re \cdot Pr$$

<Dittus and Boelter, 1930>

Use Re>10,000

for Pe>70,000

=

Re>40,000

Ⅲ. Proposal of improved S·B model [4/7]

◆ Proposal of a new NVGP model [3/4]

- Criterion issue
  - Kalitvianski, 2000; Ha et al., 2004; Ha et al., 2018
- Used the criterion by Ha et al. (2018)

$$u^* = \frac{u_i}{1.53\left(\frac{g\sigma(\rho_L-\rho_v)}{\rho_L^2}\right)^{0.25}} = 1.2,$$

where, $u_i = \dot{m}/\rho_f A.$

$$Nu = \frac{2}{\frac{11}{24}+\sum_{n=1}^{\infty} C_n exp\left(\frac{-\beta_n^2 x}{r_0}\frac{1}{Pe}\right)R_n(1)} \text{ for laminar}$$

<Siegel et al., 1958>

$$Nu = 0.0243Re^{0.8}Pr^{0.4} \text{ for turbulent}$$

<Dittus and Boelter, 1930>

Use Re>10,000

<New NVGP model>

$$Nu = \frac{1}{0.0901-0.0893\exp\left(-158\frac{1}{Pe}\right)} \text{ for } u^* \leq 1.2$$

$$Nu = 1.09(Pe \cdot Pr)^{0.5833} \text{ for } u^* > 1.2$$

|| Re>12,000

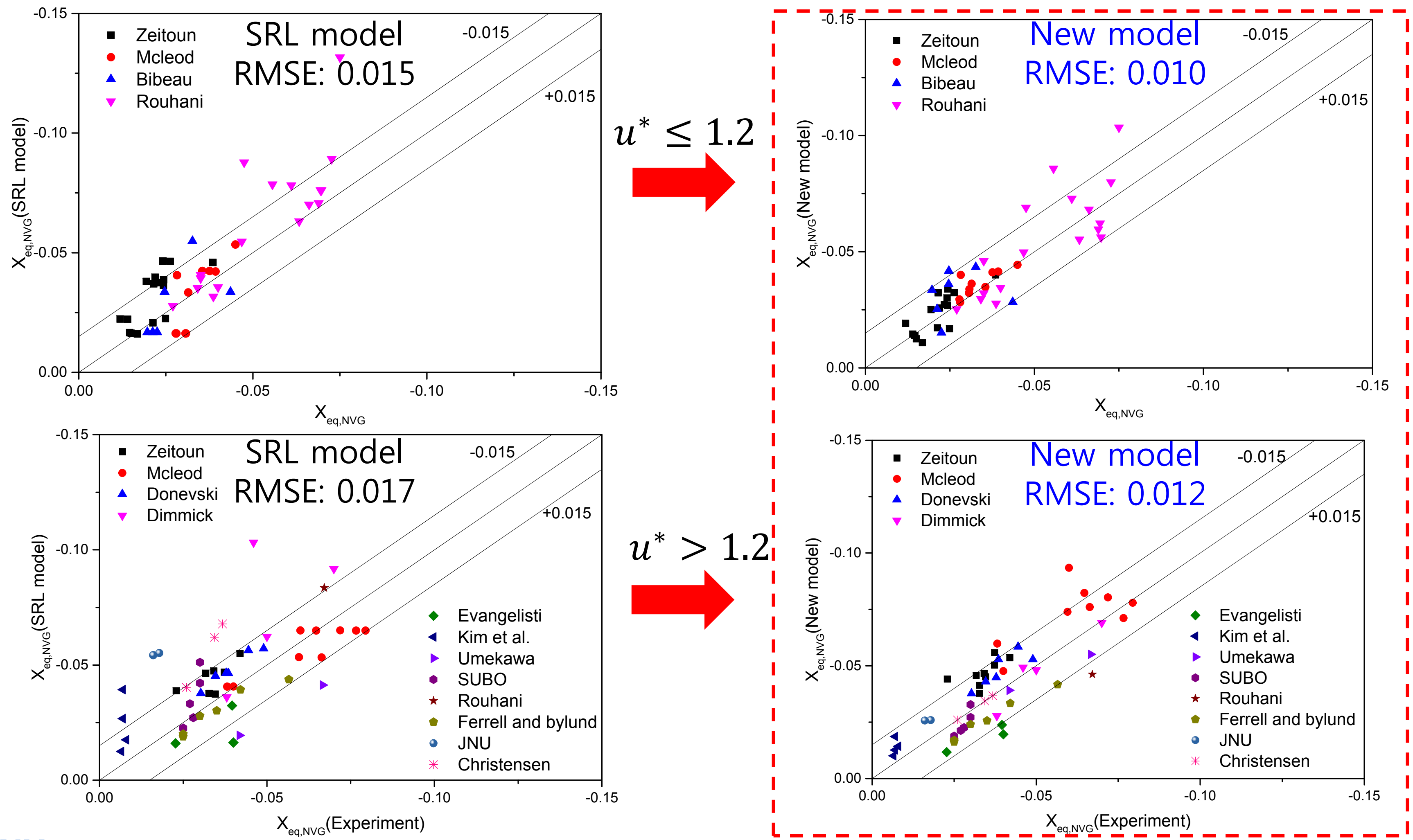
※ NVGP of 103 experimental cases was fitted.

Ⅲ. Proposal of improved S·B model [5/7]

◆ Proposal of a new NVGP model [4/4]

$$x_{eq,NVGP} = -\frac{c_{pf}(T_{sat} - T_{NVGP})}{h_{fg}}$$

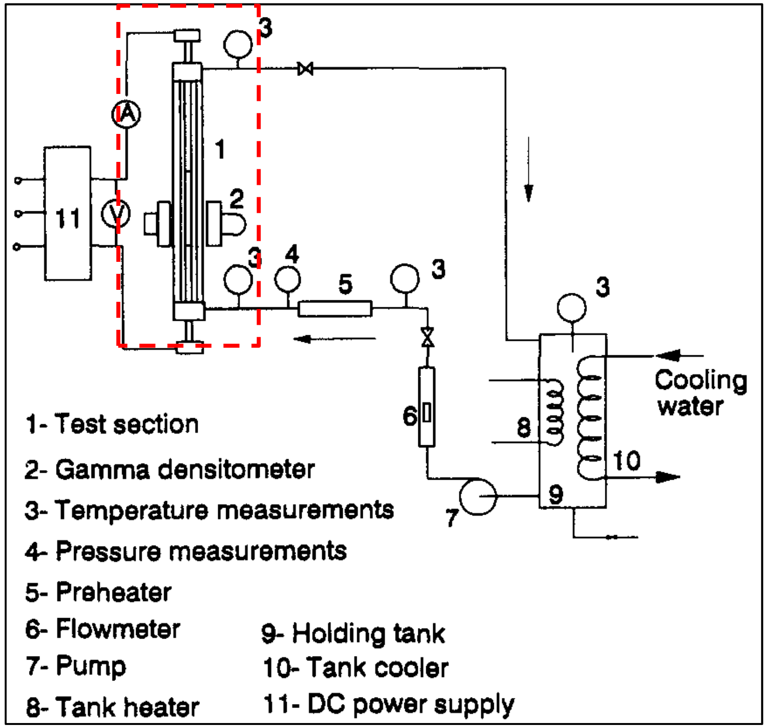
- Comparison of experimental NVGP and calculated NVGP



Ⅲ. Proposal of improved S·B model [6/7]

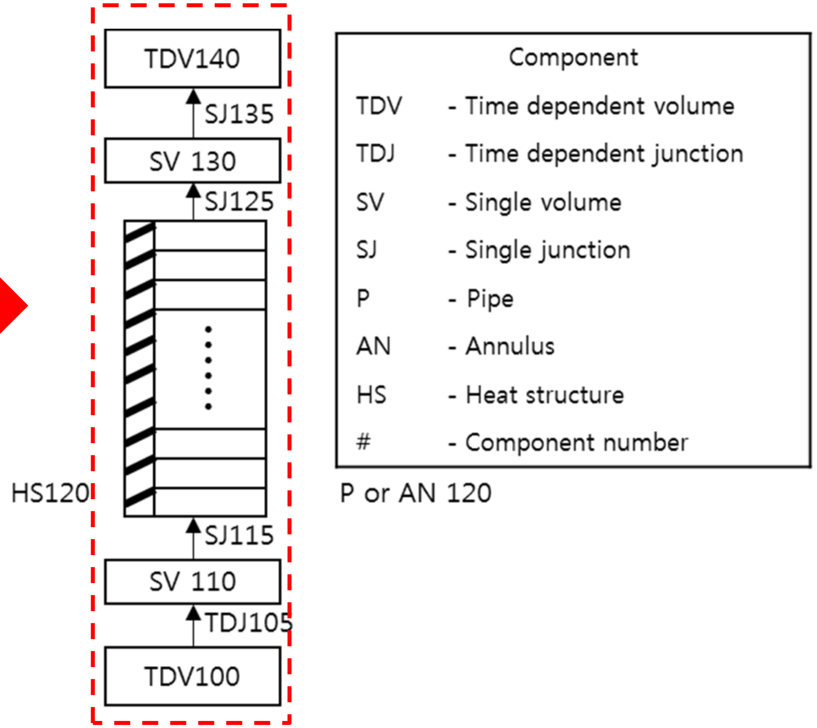
◆ Modification of wall evaporation model [1/2]

- Test loop and MARS nodalization
  - SRL Wall evaporation model was empirically modified through several times MARS cal.



<Test loop of Zeitoun experiment >

<Zeitoun, 1997>

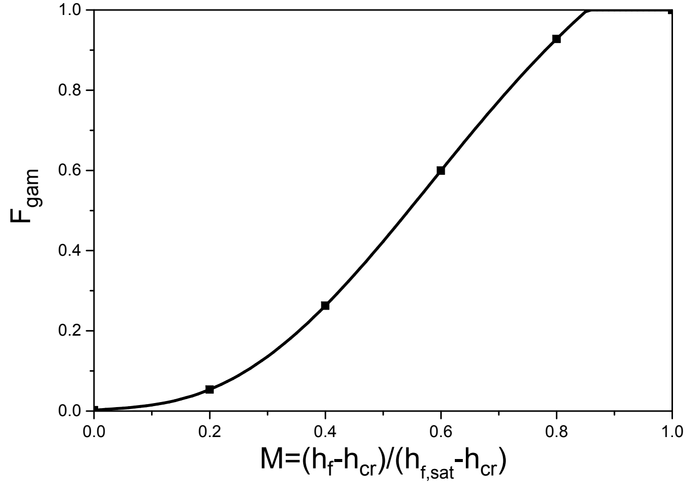


<MARS nodalization>

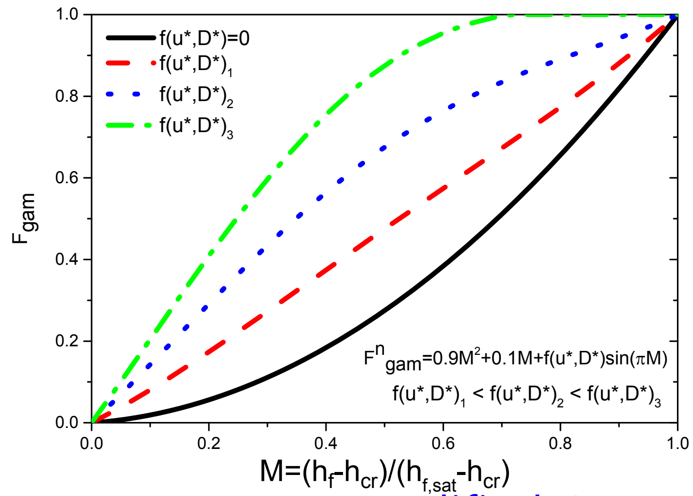
◆ Modification of wall evaporation model [2/2]

- Modification of $\boldsymbol{F_{gam}}$

  - Consider the effects of liquid velocity (u^*) and hydraulic dia.(D^*)



< $\boldsymbol{F^n_{gam}}$ vs. M; SRL>



< $\boldsymbol{F^n_{gam}}$ vs. M; modified SRL>

Model	$u^* \le 1.2$	$u^* > 1.2$
SRL wall evaporation model	$\Gamma_w = \frac{q'' A_w}{V(h_g - h_f)} \times \left(\frac{1}{1+\varepsilon_{SRL}}\right) \times \left(M + \left(\boldsymbol{F^n_{gam}} - M\right) \times F_{press}\right)$ $\boldsymbol{F^n_{gam}} = min[0.0022 + 0.11M - 0.59M^2 + 8.68M^3 - 11.29M^4 + 4.25M^5, 1.0]$	
Modified model	$\boldsymbol{F^n_{gam}} = \min[1.0, 0.9M^2 + 0.1M + \boldsymbol{f(u^*, D^*)} \sin(\pi M)]$	
	$\boldsymbol{f(u^*, D^*)}$ $= \min\left[0.091959 u^{*0.266} D^{*2}, 1.0\right]$	$\boldsymbol{f(u^*, D^*)} =$ $\min\left[0.43837 (u^* - 1.2)^{0.545} D^{*2}, 1.0\right]$

$$\boldsymbol{u^*} = \frac{u_i}{1.53\left[\frac{g\sigma(\rho_L - \rho_v)}{\rho_L^2}\right]^{0.25}}$$

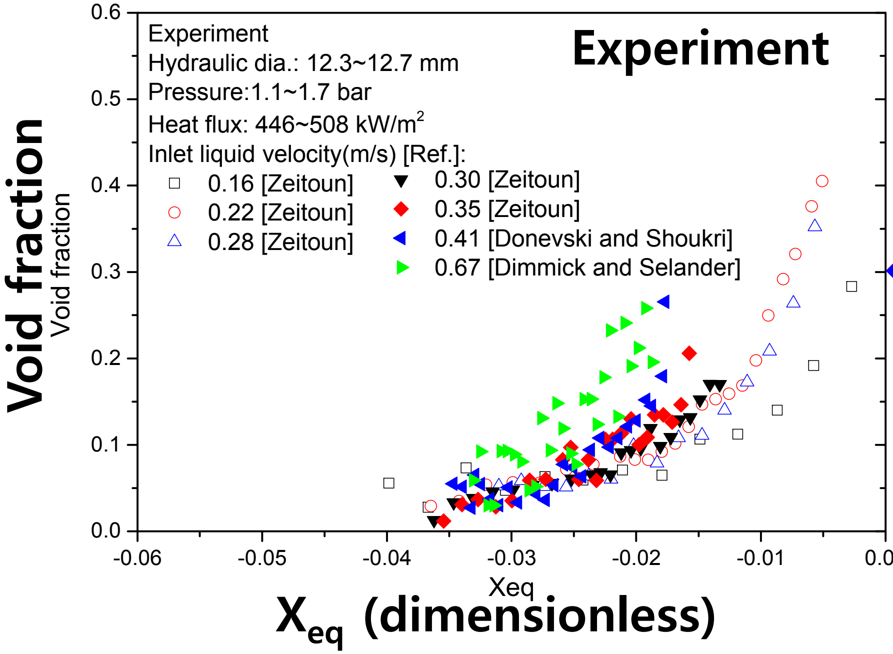
$$D^* = \frac{D_{ref.}}{D_h}$$

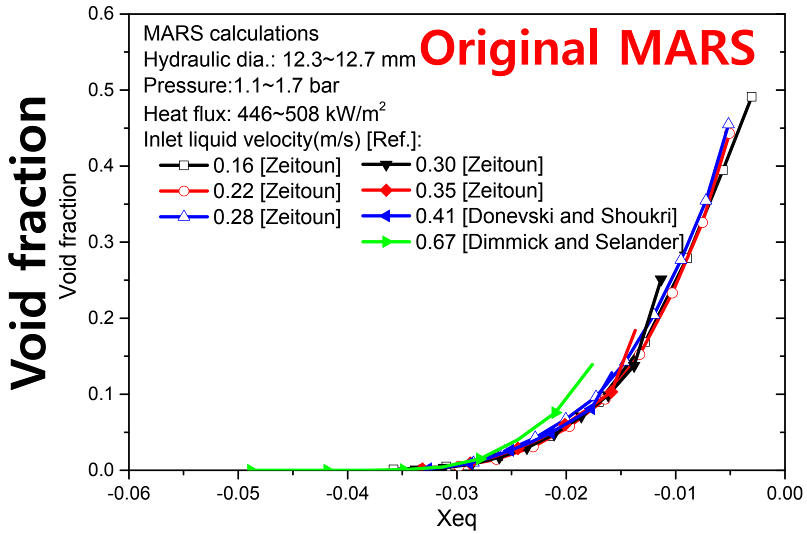
$D_{ref.}$ → 12.7mm (0.5 inch)

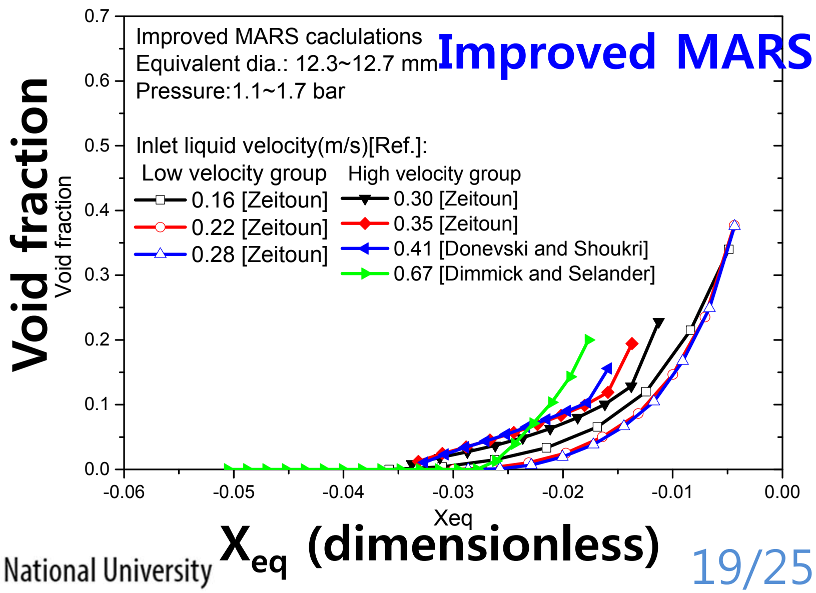
Contents

IV. Assessment of the improved S·B model [1/5]

◆ Velocity effect (Pe < 70,000)

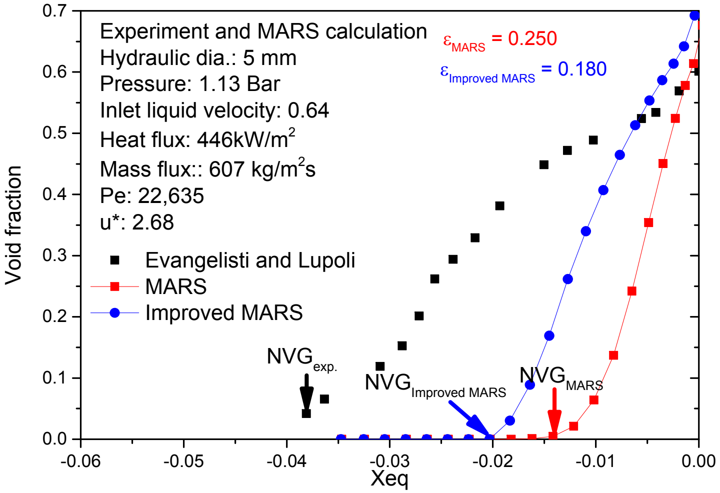


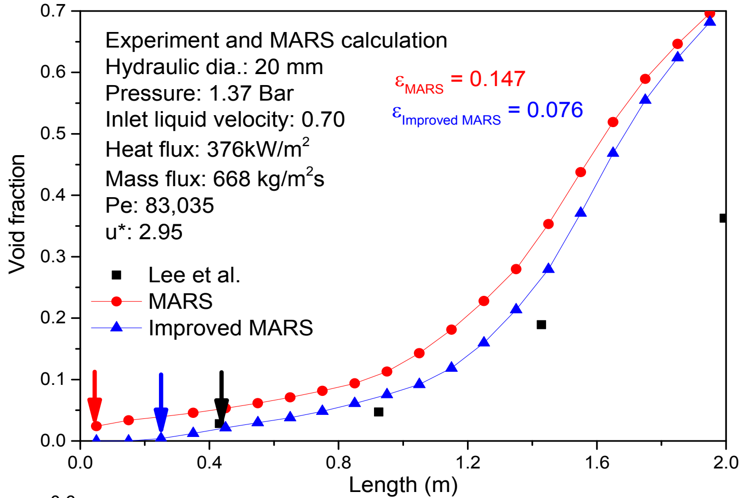


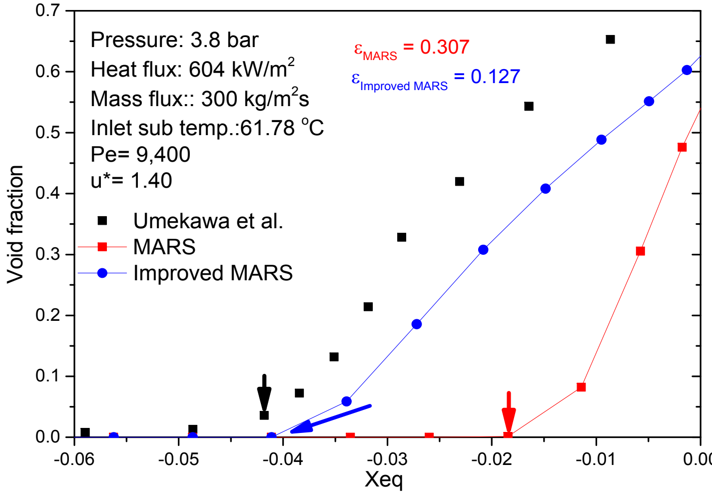


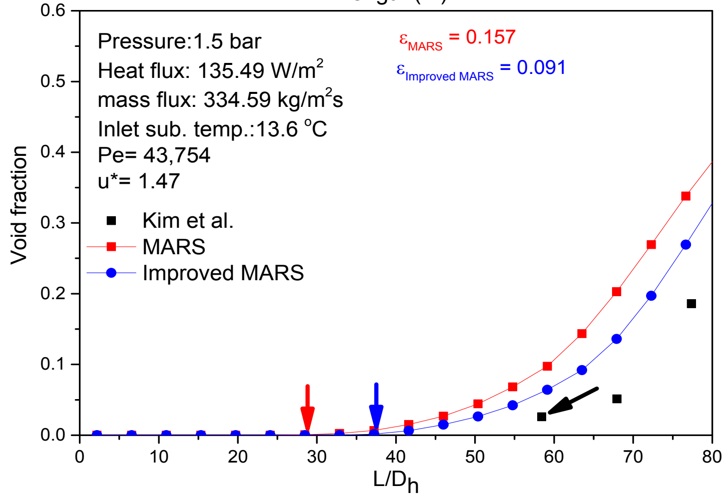
IV. Assessment of the improved S·B model [2/5]

◆ Hydraulic dia. effect









<Small diameter; $D_h = 5\ mm$>

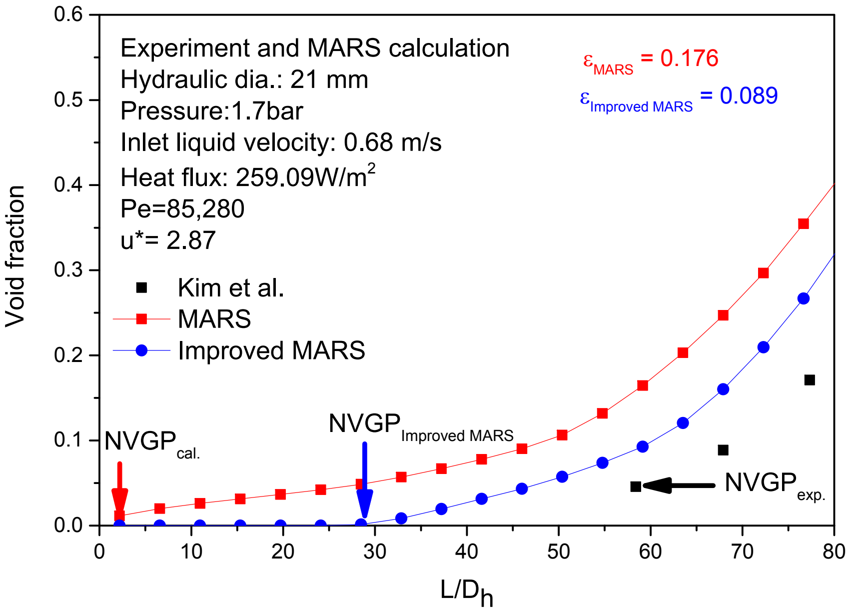
<Large diameter; $D_h = 20, 21\ mm$>

<Evangelisti and Lupoli, 1969; Umekawa et al., 2015>

<Lee et al., 2017; Kim et al., 2015>

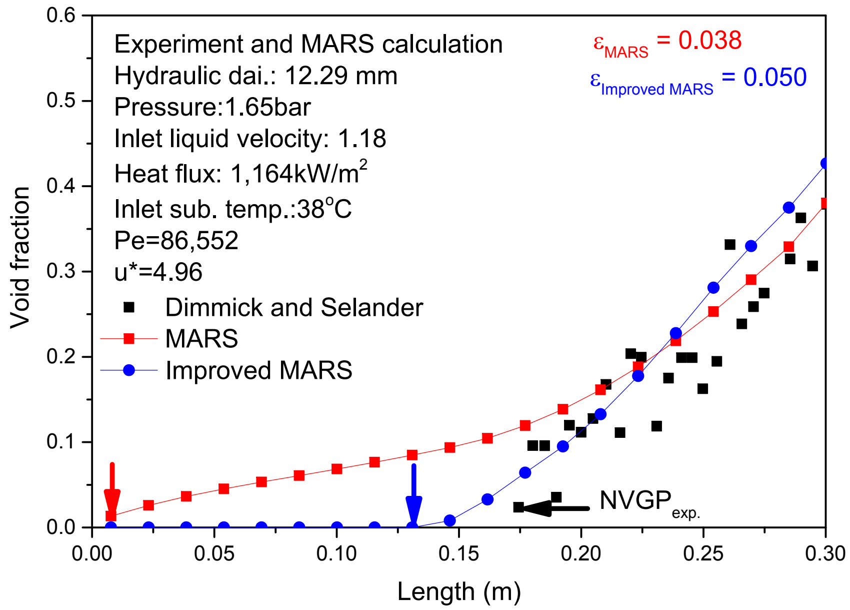
◆ Criterion for NVGP model

- ~~Pe=70,000~~ → u^*=1.2



<Pe=85,280>

<Kim et al., 2015>



<Pe=86,552>

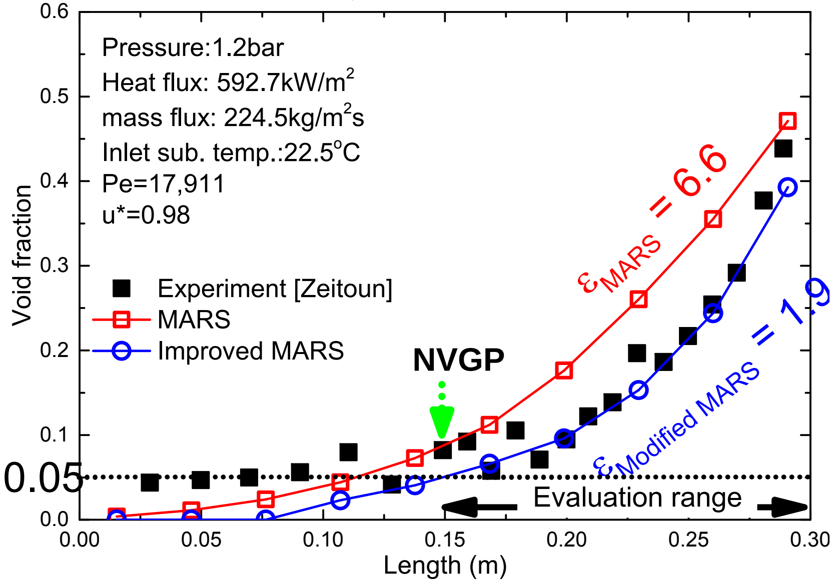
<Dimmick and Selander, 1990>

IV. Assessment of the improved S·B model [4/5]

◆ Quantitative assessment [1/2]

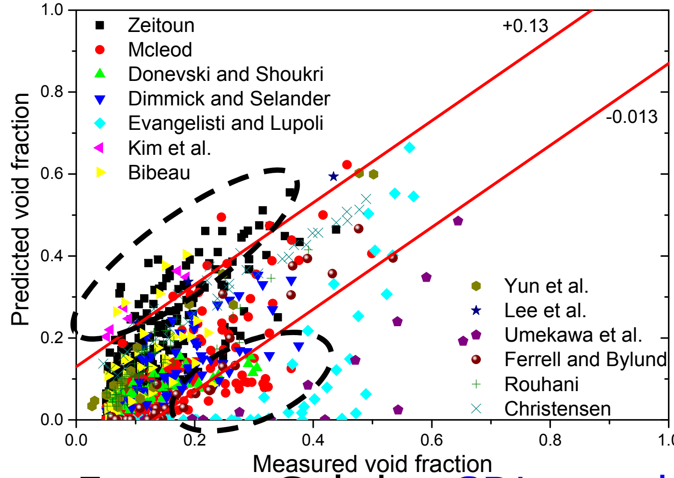
- Comparison of measured data and predicted void fraction

Example; 1 case

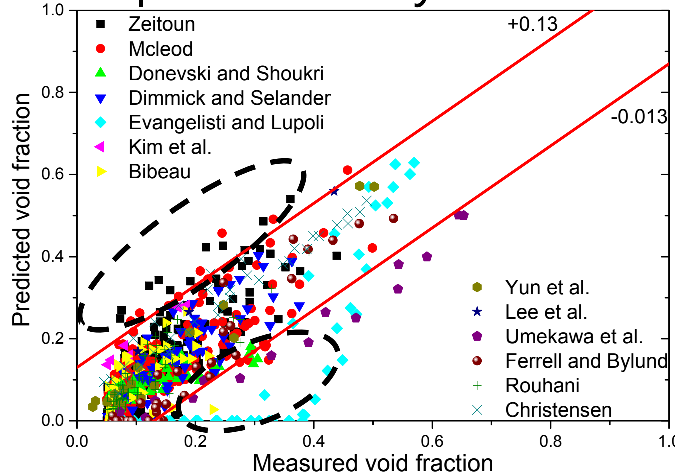


$$\varepsilon = \frac{1}{n}\sum_{i=1}^{n}\left|\alpha_{exp,i} - \alpha_{cal,i}\right|$$

Average of absolute void fraction error



<Exp. vs. Cal. by SRL model>



<Exp. vs. Cal. by improved model>

IV. Assessment of the improved S·B model [5/5]

◆ Quantitative assessment [2/2]

- A reduction of the void fraction error by **3.7 %**
- A reduction of the relative error by **34 %**

Experiment	No. of test (No. of data point)	ε_{mean}	
		MARS	Improved MARS
Zeitoun	25 (308)	0.068	**0.048**
Mcleod	19 (239)	0.079	**0.052**
Donevski and Shoukri	6 (62)	0.061	**0.041**
Dimmick	4 (59)	0.069	**0.041**
Evangelisti and Lupoli	3 (44)	0.212	**0.173**
Kim et al.	4 (6)	0.173	**0.093**
Bibeau	6 (39)	0.074	**0.055**
Yun et al.	5 (16)	0.045	**0.029**
Lee et al.	2 (3)	0.147	**0.086**
Umekawa et al.	2 (16)	0.263	**0.145**
Ferrell and Bylund	6 (30)	0.099	**0.078**
Christensen	3 (36)	0.071	**0.052**
Rouhani	18 (67)	0.029	**0.031**
Total	**103 (925)**	**0.108**	**0.071**

$$\frac{0.108-0.071}{0.108} \times 100 = 34\%$$

Contents

V. Summary

◆ Assessment of the subcooled boiling model in MARS

- Velocity effect
- Hydraulic diameter effect
- Criterion (Pe=70,000) issue for low- and high velocity

◆ Proposal of the improved subcooled boiling model

- Collected the experimental data (103 experimental cases in 13 experiments)
- Proposed a new NVG model based on the local Nusselt number
- Modified SRL wall evaporation model

◆ Assessment of the improved subcooled boiling model

- Improvement of deficiencies related to velocity/ hydraulic dia./ criterion issue
- Quantitative assessment → a reduction of relative void fraction error by 34 %

Thank you for your attention.

Q & A

APPENDICE

Appendix – References

- Bergman, T.L., Incropera, F.P., Lavine, A.S., Dewitt, D.P., 2011. Introduction to heat transfer. John Wiley & Sons.
- Bibeau, E.L., 1988. Experimental investigation of subcooled void growth for upflow and downflow at low velocities and low pressure. PhD Thesis, University of British Columbia, Vancouver, BC.
- Bowring, R.W., 1962. Physical model based on bubble detachment and calculation of steam voidage in the subcooled region of a heated channel. OECD Halden Reactor Project Report HPR-10, Institute for Atomenergi, Halden, Norway.
- Burmeister, L.C., 1993. Convective heat transfer. John Wiley & Sons.
- Christensen, H., 1961. Power-to-void transfer functions. PhD Thesis, Massachusetts Institute of Technology.
- Collier, J.G., 1981. Convective Boiling and Condensation. McGraw-Hill, New York.
- Dimmick, G.R., Selander, W.N., 1990. A dynamic model for predicting subcooled void: experimental results and model development. EUROTHERM seminar, Pisa, Italy.
- Dittus, F.W., Boelter, L.M.K. 1930. University of California publications on engineering. University of California publications in Engineering, 2, 371.
- Donevski, B., Shoukri, M., 1989. Experimental study of subcooled flow boiling and condensation in an annular channel. McMaster University, Thermofluids report no. ME/89/TFRI.
- Evangelisti, R., Lupoli, P., 1969. The void fraction in an annular channel at atmospheric pressure. Int. J. Heat Mass Transfer 12 (6), 699IN3705-704711.

Appendix – References

- Ferrell, J.K., Bylund, D.M., 1966. Low pressure steam-water flow in a heated vertical channel. Final Report Volume II on A Study of Convection Boiling Inside Channels, North Carolina State University, Raleigh. Dept. of Chemical Engineering.
- Ha, K.S., Lee, Y.B., No, H.C., 2005. Improvements in predicting void fraction in subcooled boiling. Nuclear technology 150 (3), 283-292.
- Ha, T.W., Jeong, J.J., Yun, B.J., Yoon, H.Y., 2018. Improvement of the MARS subcooled boiling model for low-pressure, low-Pe flow conditions. Annals of Nuclear Energy 120, 236-245.
- Kalitvianski, V., 2000. Qualification of CATHARE 2 V1. 5 Rev. 6 on subcooled boiling experiments (KIT test). SMTH/LMDS/EM/2000-030. CEA.
- KAERI, 2009. MARS Code Manual Volume I: Code Structure, System Models and Solution Methods. Korea Atomic Energy Research Institute, KAERI/TR-2812.
- Kim, M.O., Kim, S.J., Park, G.C., 2002. Comparison of Void Fraction Profiles in Subcooled Boiling of Low Pressure by 3D Measurement and MARS Calculation. In: Proceedings of the Korean Nuclear Society Conference, Korean Nuclear Society.
- Lahey, R.T., 1978. A mechanistic subcooled boiling model. In: Proceedings of the 6th International Heat Transfer Conference, vol. 1. Toronto, Canada.
- Lee et al., 2017. Improvement of mathematical models for low-pressure subcooled flow boiling based on the measurement of local bubble parameters. 2016M2B2A9911742, NRF.
- Levy, S., 1967. Forced convection subcooled boiling—prediction of vapor volumetric fraction. Int. J. Heat and Mass Transfer 10 (7), 951-965.

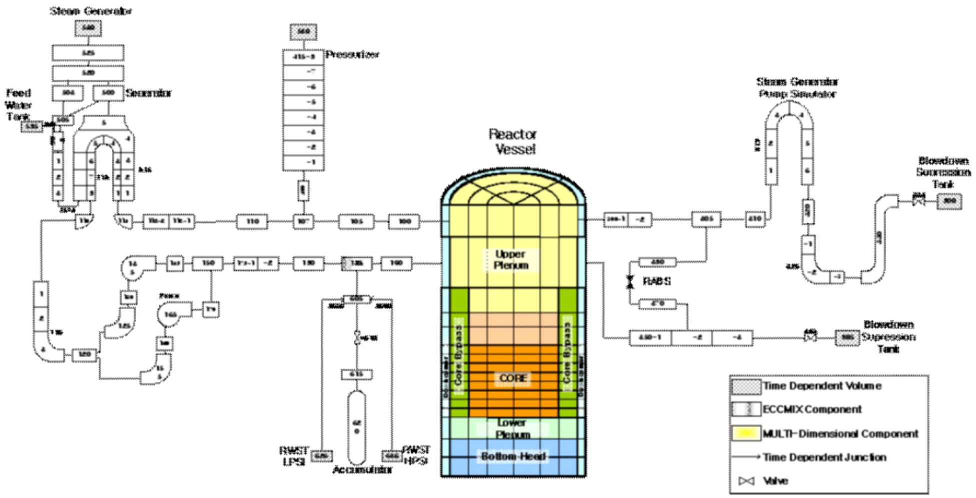
Appendix – References

- Mcleod, R. D., 1987. Investigation of subcooled void fraction growth in water under low pressure and low flow rate conditions. Master thesis, University of Carleton, Ottawa, Ont.
- Rogers, J.T., Salcudean, M., Abdullah, Z., Mcleod, D., Poirier, D., 1987. The onset of significant void in up-flow boiling of water at low pressure and velocities. Int. J. Heat Mass Transfer 30 (11), 2247-2260.
- Rouhani, S.Z. 1966. Void measurements in the regions of subcooled and low-quality boiling. Part II, report no. AE-RTL-849, AB Atomenergi.
- Sellars, J.R., Tribus, M., Klein, J. 1954. Heat transfer to laminar flow in a round tube or flat conduit: the Graetz problem extended.
- Siegel, R., Sparrow, E.M., Hallman, T.M., 1958. Steady laminar heat transfer in a circular tube with prescribed wall heat flux. Applied Scientific Research, Section A, 7(5), 386-392.
- Staub, F.W., 1968. The void fraction in subcooled boiling—prediction of the initial point of net vapor generation. Journal of Heat Transfer 90 (1), 151-157.
- Thurston, C. G., 1992. RELAP5/MOD3 benchmarks of low pressure subcooled vapor voiding in annular flow channels. Babcock & Wilcox Advanced Systems Engineering, Doc. 51-3001526-00.
- Umekawa, H., Nakamura, S., Fujiyoshi, S., Ami, T., Ozawa, M., Saito, Y., Ito, D. 2015. The influence of the heating condition on the void fraction in a boiling channel. Physics Procedia 69, 599-606.
- Yun, B.J., Bae, B.U., Euh, D.J., Song, C.H., 2010. Experimental investigation of local two-phase flow parameters of a subcooled boiling flow in an annulus. Nucl. Eng. Des. 240 (12), 3956-3966.
- Zeitoun, O., Shoukri, M., 1997. Axial void fraction profile in low pressure subcooled flow boiling. Int. J. Heat and Mass Transfer 40 (4), 869-879.

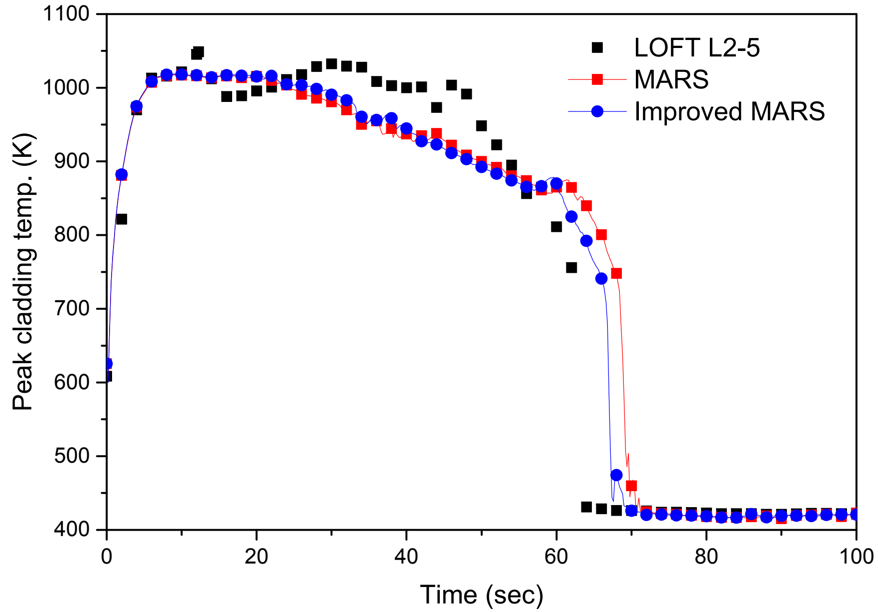
IV. Assessment of the improved S·B model [6/6]

◆ Future plan

- How can the improved S·B model be utilized for the safety analysis?



<LOFT L2-5 Nodalization>



<LOFT L2-5 calculation>
<by J.H.Lee>

The end