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Improvement of the MARS subcooled boiling model for the prediction of OFI

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1. Introduction

When considering heated channels with subcooled liquid flow, one limiting issue for reliable and safe operations is related to the possible generation of vapor with the consequent onset of the Ledinegg instability [1]. The onset of flow instability (OFI) is one of Ledinegg instability. Many studies have confirmed that the onset of flow instability(OFI) can occur in small module reactors and research reactors, which have narrow flow channels in the reactor core [2,3]. Because the onset of flow instability can cause premature critical heat flux(CHF), mechanical vibration and instability of system operation, accurate prediction is needed.

From decades ago, some studies have been performed to predict OFI using the MARS code [4]. However, it was known that the present models yield conservative results in the OFI prediction [5].

In the MARS code, the subcooled boiling model consists of several sub-models, including the net vapor generation(NVG) model, the wall evaporation model, and the surface condensation model [6]. Because the OFI occurs after the NVG, the bubble generation point is very important for the OFI prediction [7].

In this paper, a new model, which is based on the original NVG model and wall evaporation model, is proposed. The new model is proposed for a more accurate prediction of OFI. These are implemented in MARS, and the results are discussed.

2. Subcooled boiling model of MARS code

2.1. The original model

In MARS, the subcooled boiling model includes the NVG model for predicting a bubble generation point and the wall evaporation model used as a heat partitioning model. The point of net vapor generation(PNVG) is defined as a point where bubbles are rapidly increased past an onset of nucleate boiling(ONB) point where bubbles are generated for the first time.

Saha and Zuber suggested a model for void fraction and NVG point during the subcooled boiling [8]. In MARS, the SRL model that is similar to the model proposed by Saha and Zuber is adopted. The SRL model comprises the NVG model and the wall evaporation model. The NVG models are as follows:

$$Nu = \frac{\ddot{q}D_h}{k_f\,(T_{sat} - T_{NVGP})} = 455 \quad , \qquad \text{for Pe} \le 70{,}000 \quad (1)$$

$$St = \frac{Nu}{Re\cdot Pr} = \frac{\ddot{q}}{Gc_{pf}\,(T_{sat} - T_{NVGP})} = 0.0055 - 0.0009F_{press}$$

$$\text{for Pe} > 70{,}000 \quad (2)$$

$$Pe = Re\cdot Pr = \frac{GD_h}{\mu}\cdot\frac{C_{pf}\,\mu}{k} = \frac{GC_{pf}}{k}\ ,$$

T_{PNVG} is the bulk liquid temperature at PNVG,

$$\mathrm{F_{press}} = \frac{1.0782}{1.015 + \exp[(\mathrm{P/P_{psia}}\ \text{-}140.75)/28.0]}\ ,$$

$\mathrm{F_{press}}$ is a pressure dependent multiplier.

$\mathrm{P_{psia}} = 6.894\times10^3$ for units conversion.

$$h_{cr} = \begin{cases} h_{f,sat} - St\,\dfrac{C_{pf}}{(0.0055 - 0.0009\times F_{press})}\,(for \quad Pe > 70{,}000) \\ h_{f,sat} - Nu\,\dfrac{C_{pf}}{455} \qquad\qquad (for \quad Pe \le 70{,}000) \end{cases} \quad (3)$$

The PNVG is determined by the enthalpy value calculated by equation (3). With a ratio of enthalpy obtained by equation (3), bubble generation rate is calculated by a wall evaporation model. The wall evaporation model is as follows:

$$\Gamma_{\mathrm{W}} = \frac{q_w\cdot A_w}{V\cdot h_{fg}}\left(\frac{1}{1+\varepsilon_{SRL}}\right)\Big[Mul + F_{press}\left(F_{gam} - Mul\right)\Big] \quad (4)$$

$$Mul = \frac{h_f - h_{cr}}{h_{f,sat} - h_{cr}}\ ,$$

$$\mathrm{F_{gam}} = \min[1.0, 0.0022 + 0.11\mathrm{Mul} - 0.59\mathrm{Mul}^2 + 8.68\mathrm{Mul}^3 - 11.29\mathrm{Mul}^4 + 4.25\mathrm{Mul}^5] \quad (5)$$

where the quantity $\varepsilon_{\mathrm{SRL}}$ is the pumping factor, to correct the effect of the density ratio at the low-pressure condition, which is calculated by the code as

$$\varepsilon_{\mathrm{SRL}} = \frac{\rho_{\mathrm{f}}\,(h_{f,sat} - \mathrm{h_f})\times\mathrm{F_{eps}}}{\rho_{\mathrm{g}}\mathrm{h_{fg}}} \quad (6)$$

$$\mathrm{F_{eps}} = \min\left[1.0, \frac{1.0}{0.97 + 38.0 \times \exp[-(\mathrm{P}/\mathrm{P_{psia}} + 60.0)/42]}\right] \tag{7}$$

, F_{eps} is a pressure dependent multiplier.

Finally, the energy equation is calculated using the wall vapor generation rate per unit volume Γ_w .

2.2. Assessment of original subcooled boiling model

It has been known that the NVG model is conservatively used to predict OFI. To evaluate the prediction performance of the NVG model, experimental data with various geometry were collected [9-15].

Table I: Onset of Flow Instability experimental data

Exper-imental	No. of data	Geometry Type	Flow Direction	Gap (mm)	Width (mm)	$T_{l,in}$ (℃)	P_{out} (bar)
Whittle-Forgan1	17	Rectangular	Up	3.23	25.4	35~65	1.16
	13						
	7		Down				
W&F2	16		Up	2.44		45~65	1.16/1.7
W&F3	15			2.03		35~75	1.16
W&F4	12			1.39		35~65	1.16
W&F5	9	Pipe		d=6.45		45~65	1.16
THTL	7	Rectangular		1.27	12.7	40~45	1.75 ~ 17.23
	4				25.7		
Kennedy	26	Pipe	Horizontal	d=1.45, 1.17		50	3.45 ~ 10.34
Stelling	10	Pipe	Down	d=9.14~25.27		25	4.48
Stoddard	43	Annular pipe	Horizontal	$d_{In} = 6.4$ $d_{out} = 7.7 \sim 8.2$		27~68	3.39 ~ 10.37
Vernier	3	Rectangular	Up	2	53	22~33	2.36
Total	182	-	-	1.39 ~ 3.23	12.7 ~ 53	22~75	1.16 ~ 17.23

Table II: Quantitatively evaluation of each test case

Experiment	Gap size (mm)	No. of test	MPE (%)
W&F 1 [9,10]	3.23	37	6.59
W&F 2 [9,10]	2.44	16	5.10
W&F 3 [9,10]	2.03	15	-1.92
W&F 4 [9,10]	1.39	12	-4.85
W&F 5 [9,10]	d = 6.29	9	-1.05
THTL [11]	1.27	11	-3.55
Kennedy [12]	d = 1.17 d = 1.15	19 7	-0.39 -3.13
Stelling [13]	d = 9.14 ~ 25.27	10	-5.88
Stoddard [14]	$d_{In} = 6.4$ $d_{out} = 7.7 \sim 8.2$	43	-1.14
Vernier [15]	2.0	3	-4.42
Total		182	MAPE(%) 5.37

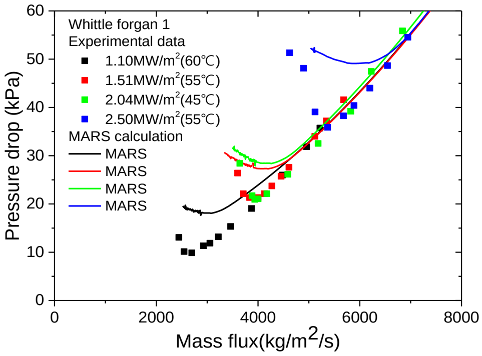


Fig. 1. The comparison of experimental data and calculated result.

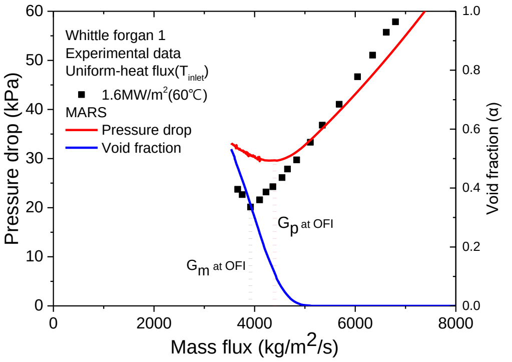


Fig. 2. Mass flux and void fraction at OFI

Fig. 1 compares the experimental values of W&F1 among the collected experimental data with the MARS calculation results. In general, the onset of flow instability(OFI) is a minimum pressure drop point in pressure drop versus flow rate characteristic (a demand curve) [16]. Fig. 2 shows a mass flux at OFI of experiment and calculation. A ratio of mass flux at OFI is as follows :

$$G\_ratio = \frac{Gp(\text{calculation})}{Gm(\text{experiment})} \tag{8}$$

Experimental and calculated values were compared for all experimental data. The mean percentage error (MPE) and the mean absolute percentage error (MAPE) was used to evaluate each OFI test quantitatively, and the assessments are summarized in Table II. They are defined as follows :

$$MPE(\%) = \frac{100}{N}\sum_{i=1}^{N}\frac{x_i - f_i}{x_i} \tag{9}$$

$$MAPE(\%) = \frac{100}{N}\sum_{i=1}^{N}\left|\frac{x_i - f_i}{x_i}\right| \tag{10}$$

where f_i is the calculated value and x_i is the experimental data. W&F test of table II shows that the original model cannot consider the effects of the gap size.

3. New model through modification of the subcooled boiling model

3.1. Factors affecting an OFI Prediction

The effects of Gap size can be seen in the aspect ratio (b/a) versus G ratio graph (Fig. 3). If the aspect ratio is increasing, OFI tends to be predicted from high mass fluxes.

Froude number, a dimensionless number, can be expressed in terms of gravity and hydraulic diameter as follows:

$$Fr = \frac{V}{\sqrt{gL}} = \frac{G^2}{\rho_l^2 g D_h} \tag{11}$$

The effects of gravity and hydraulic diameter can be seen in the Froude number versus G ratio graph (Fig. 4). In each W&F test case, if the Fr number is large, the OFI tends to be predicted from high mass fluxes.

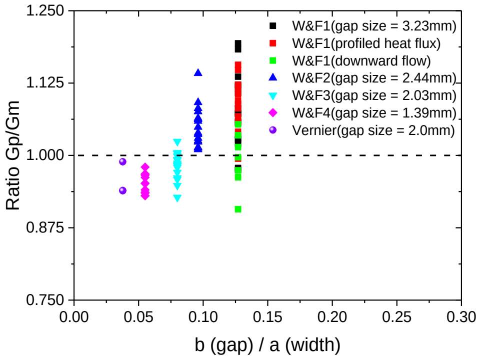


Fig. 3. The effect of aspect ratio on OFI

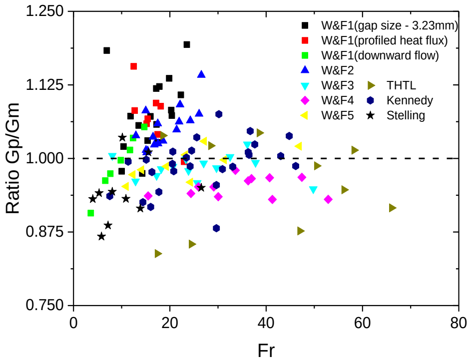


Fig. 4. The effect of Fr on OFI

3.2. Modification of original models and Assessment

Fig. 2 shows that the PNVG exists before the OFI. Accordingly, if the NVG model is modified, the OFI can be predicted more accurately. In a conventional NVG model, the Nusselt number is constituted of a function for Reynolds number, Prandtl number and Stanton number. To consider the factors affecting the OFI, the aspect ratio and Froude number were added to the existing function. To correct the NVG model calculating the bubble generation point, the OFI values of the experiments were plotted in the graph of Nusselt number versus the function of dimensionless number. Fig. 5 shows two major trends. W&F, THTL, Stelling and Vernier are vertical channel experiments and Kennedy are horizontal tube experiment.

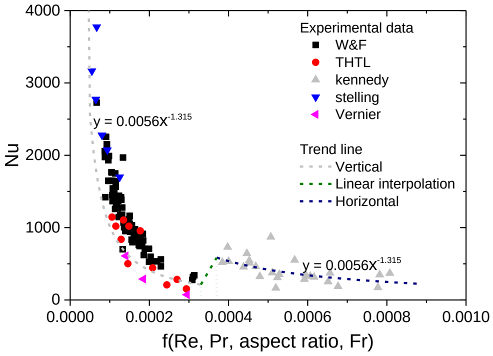


Fig. 5. Nu vs. X at OFI

X, a function of Re, Pr, aspect ratio(b/a) and Fr, is found using the least squares method and it is defined as follows:

$$X = \frac{Fr^{0.03} abs\left(0.5 - \frac{b}{a}\right)}{\mathrm{Re}^{0.7}\,\mathrm{Pr}^{0.6}} \tag{12}$$

According to the trend of the experimental data in Fig. 5, two trend lines can be determined. However, there are sections where experimental trends of vertical and horizontal tubes are discontinuous. A simple method, linear interpolation, was applied to estimate trends in this section. The NVG Model was modified according to the trend lines. The wall evaporation model was also modified to consider the aspect ratio, hydraulic diameter and heat flux. The new model is shown in Table III.

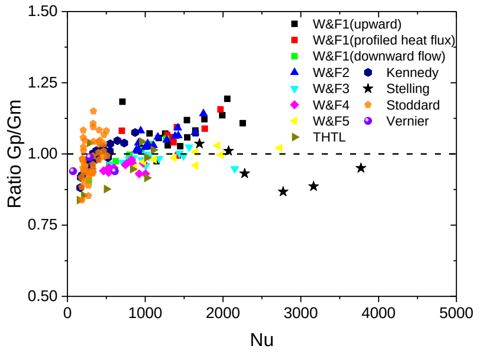
Table III: New model

<table>
<tr><th rowspan="2">Model</th><th colspan="3">Correlations</th></tr>
<tr><th>$X \le 0.00033$</th><th>$0.00033 < X \le 0.00037$</th><th>$X > 0.00037$</th></tr>
<tr><td>Modified NVG</td><td>$Nu = 178.57 \times \mathrm{Re}^{0.92}\,\mathrm{Pr}^{0.79} \times Fr^{-0.039}(\mathrm{b/a})^{-1.3}$</td><td>Linear interpolation</td><td>$Nu = 10.92 \times \mathrm{Re}^{0.77}\,\mathrm{Pr}^{0.66} \times Fr^{-0.033}(\mathrm{b/a})^{-1.1}$</td></tr>
<tr><td>Modified Wall evaporation</td><td colspan="3">$\Gamma_W = \frac{q_w \cdot A_w}{V \cdot h_{fg}}\left(\frac{1}{1+\varepsilon_{SRL}}\right)\left[Mul + F_{press}\left(F_{gam} - Mul\right)\right]$
where,
$\mathrm{F_{gam}} = \min[1.0, 0.0022 + 0.11\mathrm{Mul} - 0.59\mathrm{Mul}^2 + 8.68\mathrm{Mul}^3 - 11.29\mathrm{Mul}^4 + 4.25\mathrm{Mul}^5 + 0.1(\mathrm{qf}^2 \times \mathrm{gef} \times \mathrm{df}^{1.2}) \times \sin(\pi \mathrm{Mul})]$
$\mathrm{qf} = \min(5.0, \max(1, \frac{\ddot{q}}{2.5\mathrm{MW/m^2}})$
$\mathrm{gef} = \min(5,0, \max(-1.2, (-166 \times \frac{b}{a} + 14.7))$
$\mathrm{df} = \min(7.0, \max(0.6, \frac{D_h}{0.0055}))$</td></tr>
</table>

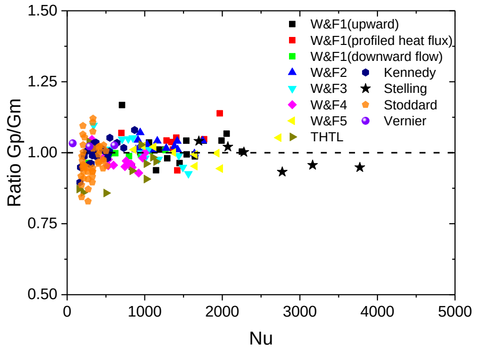
The experimental data were evaluated using the original and new models. The predictability of each model was compared in the graph of G_ratio versus the Nusselt number (Fig. 6). Standard deviations were used to quantitatively evaluate the original and new models. The standard deviation is defined as follows :

$$\sigma = \sqrt{\frac{1}{n}\sum_{1}^{n}(G_{ratio}-1)^2} \qquad (13)$$

The evaluation results are shown in Table IV.



(a) MARS_original model



(b) MARS_New model

Fig. 6. The comparison of calculated result

Table IV: Quantitatively evaluation of each model

	Standard deviation(σ)	MAPE (%)
MARS Original	0.0679	5.37
MARS New	0.0564	4.19

4. Conclusions

A new model for the prediction for the OFI is proposed by modifying the subcooled boiling model in the MARS code. The new model has been compared to the original model. The original model cannot consider the gap size effect, but the new model can capture the effect successfully. The results of the comparison show that the new model predicts the OFI more accurately than the original model.

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