Improvement of the subcooled boiling model for the prediction of the onset of flow instability in an upward rectangular channel

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1. Introduction

The occurrence of two-phase flow instability is not desirable in boiling, condensing, and other two-phase flow systems. Ledinegg instability or onset of flow instability (OFI) is an example of two-phase flow instability in which flow undergoes a sudden, large-amplitude excursion to a new, stable operating condition. Such phenomena may cause mechanical vibration and generate premature critical heat flux (CHF) of the system, therefore, limiting the reliability and safety of the system's operation [1-4]. Considering the effect of the OFI, it is important to predict the OFI point accurately.

Numerous studies to assess the criteria to identify the OFI has been done. Criteria based on the net vapor generation (NVG), is found to predict the OFI conservatively [5, 6]. The use of RELAP5/3.2 to predict the OFI in parallel channel shows the influence of uncertainty related to the inlet subcooling, heat flux, and hydraulic diameter [7]. The MARS code also shows conservative result in predicting the OFI [8].

RELAP5 [9] and MARS [10] code have similar subcooled boiling model that consists of the NVG model, wall evaporation model, interfacial condensation heat transfer, et al.

This paper aims to improve the OFI prediction of the MARS code to extend its applicability for a reactor that uses plate-type nuclear fuel. The MARS code is assessed against several experiments at different thermal-hydraulic conditions and geometries. The result of the assessment is then used to propose a modified subcooled boiling model to improve the OFI prediction of the MARS code.

2. Assessment of the OFI prediction using the MARS code

2.1. Description of the subcooled boiling model in the MARS code

As previously mentioned, the MARS code's subcooled boiling model consists of the NVG model that determines the subcooled water temperature of NVG which later referred to as the point of net vapor generation (PNVG), wall evaporation model that determines the bubble generation rate on the surface of the heating wall and interfacial condensation heat transfer that determines the bubble condensation rate surrounded by subcooled liquid.

The original NVG model was developed by Saha-Zuber [11]. However, the Savannah River Laboratory (SRL) model developed from the Saha-Zuber correlation has been used in most thermal-hydraulic codes. The SRL model consists of the NVG model and and wall evaporation model. The NVG model is represented as:

$$h_{cr} = \begin{cases} h_{f,sat} - \dfrac{1}{455}\dfrac{q''c_{pf}D_h}{k_f} & \text{for } Pe \le 70,000 \\ h_{f,sat} - \dfrac{1}{0.0055 - 0.0009F_{\text{Press}}}\dfrac{q''}{G} & \text{for } Pe > 70,000 \end{cases} \tag{1}$$

The wall evaporation model is given as:

$$\Gamma_w = \frac{q''A_{heat}}{Vh_{fg}}\left(\frac{1}{1+\varepsilon_{SRL}}\right)\left(M + F_{SRL}\right) \tag{2}$$

where

$$M = \frac{\min\left(h_f, h_{f,sat}\right) - h_{cr}}{h_{f,sat} - h_{cr}} \tag{3}$$

$$\varepsilon_{SRL} = \frac{\rho_f}{\rho_g}\frac{h_{f,sat} - \min\left(h_f, h_{f,sat}\right)}{h_{fg}}F_{eps} \tag{4}$$

$$F_{SRL} = F_{\text{Press}}\left(F_{Gam} - M\right) \tag{5}$$

$$F_{Eps} = \min\left[1.0, \frac{1.0}{0.97 + 38.0 \times \exp\left[-\left(\frac{P}{6.894\times10^3} + 60\right)\Big/42\right]}\right] \tag{6}$$

$$F_{\text{Press}} = \frac{1.0782}{1.015 + \exp\left[\left(\frac{P}{6.894\times10^3} - 140.75\right)\Big/28\right]} \tag{7}$$

$$F_{Gam} = \min\begin{pmatrix} 1.0, 0.0022 + 0.11M - 0.59M^2 + 8.68M^3 \\ -11.29M^4 + 4.25M^5 \end{pmatrix} \tag{8}$$

2.2. The OFI predictions of the MARS code

The MARS code is then assessed against collected data of OFI experiments [10-13]. The details of the experiment are listed in Table 1.

Quantitative evaluation is provided by the means of G_{Ratio} and mean absolute percentage error (MAPE). G_{Ratio} is defined as the ratio between OFI mass flux obtained from the MARS calculation (G_{MARS}) to OFI mass flux from the experiment ($G_{Experiment}$):

$$G_{Ratio} = \frac{G_{MARS}}{G_{Experiment}} \quad (9)$$

If G_{Ratio} is greater than one, the OFI is over-predicted while less than one means the OFI is under-predicted. The MAPE is defined as:

$$MAPE = \frac{1}{N}\sum_{i=1}^{N}\left|\frac{G_{MARS,i} - G_{Experiment,i}}{G_{Experiment,i}}\right| \quad (10)$$

Table 1. Collected OFI experiment.

Experiment	Geometry	Diameter (mm)		Heat flux (MW/m^2)	$T_{in,sub}$ (°C)	P (bar)	Data points
		Gap (mm)	Width (mm)				
W-F 1 [12, 13]	Rectangular	3.23	25.4	0.82 - 2.50	44 - 69	1.17	24
W-F 2 [12, 13]		2.44	25.4	1.23 - 2.50	39 - 71	1.17 - 1.72	16
W-F 3 [12, 13]		2.03	25.4	0.66 - 2.89	39 - 69	1.17	12
W-F 4 [12, 13]		1.4	25.4	0.67 - 2.26	39 - 69	1.17	12
Vernier [14]		2	53.0	0.68 - 3.15	54 - 105	2.35	4
THTL 1 [15]		1.27	12.7	0.7 - 6.4	75 - 166	1.75 - 17	6
THTL 2 [15]		1.27	25.7	2.3 - 6.5	160 - 164	16.8 - 17.3	4
W-F 5 [12, 13]	Pipe	6.45		0.86 - 3.48	39 - 59	1.17	9

The result of quantitative assessment is shown in Table 2. It shows that the code can predict the OFI in a pipe reasonably well. However, the code failed to predict the OFI in a rectangular channel as it has average MAPE of 8.22 %. The THTL-1 which has the smallest hydraulic diameter among all narrow rectangular channel has the highest MAPE of 18.14%, therefore, confirm that the hydraulic diameter has significant influence in predicting the OFI. Moreover, Figure 1 shows that the code tends to over-predict the OFI at large hydraulic diameter and under-predict the OFI at small hydraulic diameter. Figure 2 also shows the effect of heat flux as the code seems to unde-predict the OFI at large heat flux.

The relation between the Stanton and Peclet number, which are the dimensionless number in Eq. (1) is also assessed. Figure 3 shows that the current model unable to predict the Stanton number in a rectangular channel well. Figure 4 shows the effect of hydraulic diameter as the average Stanton number tends to decrease as the hydraulic diameters get smaller. It also suggests that the limiting criteria at Pe = 70,000 should be changed for a rectangular channel.

Table 2. The MAPE of the OFI mass flux experiments.

Experiment	Diameter (mm)		Hydraulic diameter (mm)	Data points	MAPE (%)
	Gap (mm)	Width (mm)			
W-F 1 [12, 13]	3.23	25.4	5.72	24	7.76
W-F 2 [12, 13]	2.44	25.4	4.45	16	10.34
W-F 3 [12, 13]	2.03	25.4	3.76	12	5.83
W-F 4 [12, 13]	1.4	25.4	2.65	12	6.95
Vernier [14]	2	53.0	3.85	4	6.98
THTL 1 [15]	1.27	12.7	2.37	6	18.14
THTL 2 [15]	1.27	25.7	2.45	4	10.62
W-F 5 [12, 13]	6.45		6.45	9	3.43
Total	Include pipe		2.37 – 6.45	87	8.22
	Exclude pipe		2.37 – 5.72	78	8.77

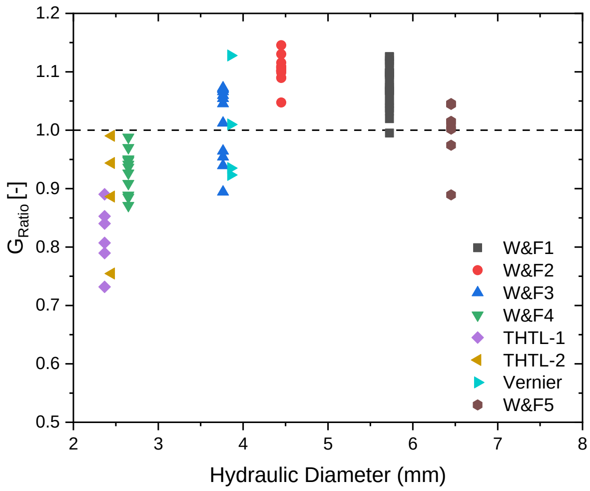


Figure 1. Effect of hydraulic diameter on the OFI prediction.

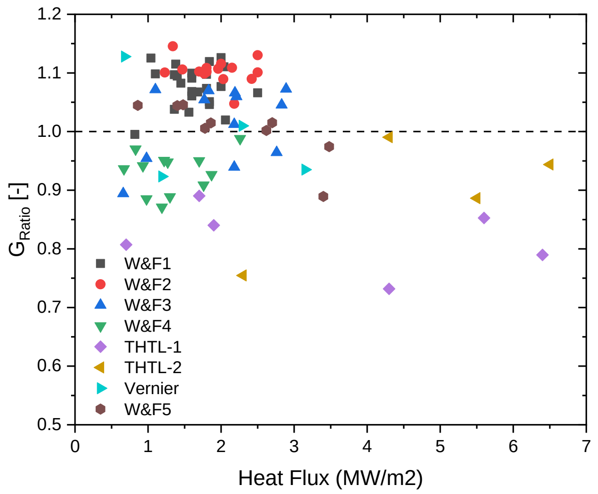


Figure 2. Effect of heat flux on the OFI prediction.

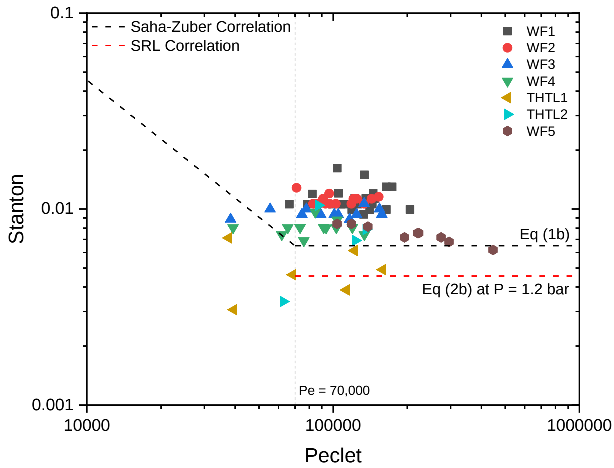


Figure 3. St-Pe relation and the original NVG model.

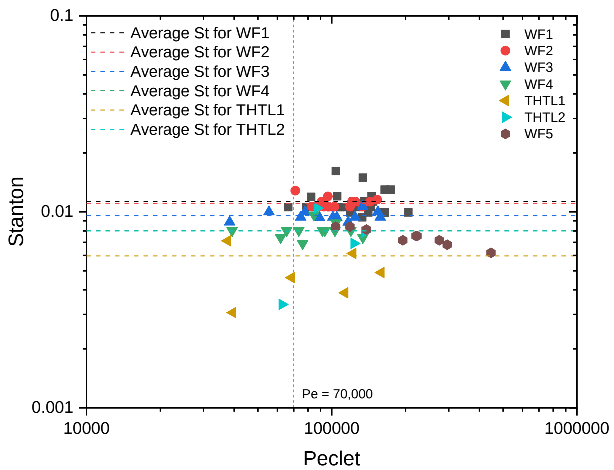


Figure 4. The effect of hydraulic diameter on St-Pe relation.

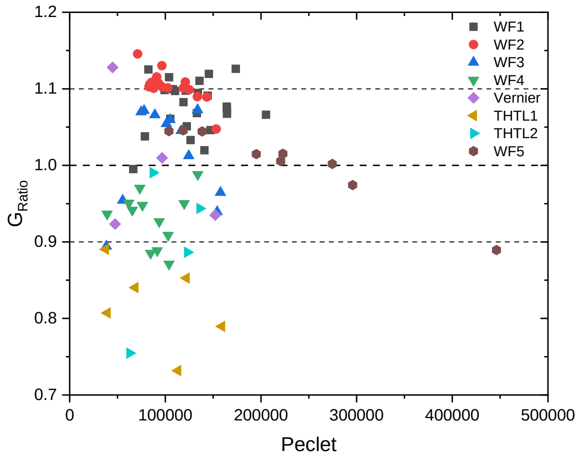
3. Improvement of the subcooled boiling model

3.1. Improvement of the NVG model

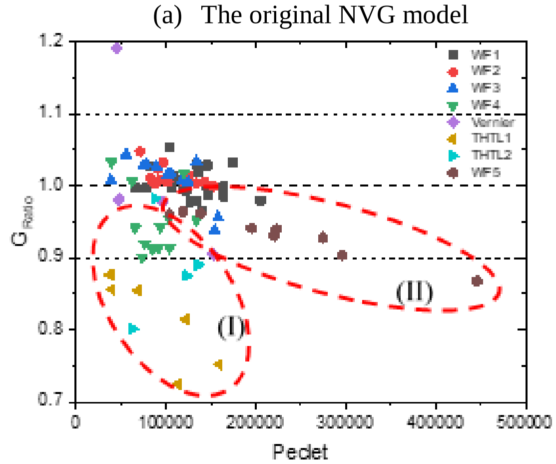
Based on the limitation of the original NVG model discussed in Section 2.2, we proposed a modification that will take the effect of the hydraulic diameter by introducing D_{Rat} and also changed the limiting criteria from Pe = 70,000 to Pe = 36,000. The modified NVG model is shown as follows:

$$h_{cr}=\begin{cases} h_{f,sat}-\dfrac{1}{399D_{Rat}^{1.4}}\dfrac{q''c_{pf}D_h}{k_f} & \text{for } Pe\le 36{,}000 \\ h_{f,sat}-\dfrac{1}{0.00834-0.00133F_{Press}}\dfrac{q''}{G\cdot D_{Rat}^{1.4}} & \text{for } Pe>36{,}000 \end{cases} \tag{11}$$

where $D_{Rat}=\min\left(1.0,\dfrac{D_h}{0.0045}\right)$.



(a) The original NVG model



(b) The modified NVG model.

Figure 5. Comparison of the OFI prediction.

Figure 5 shows the comparison between the original and the modified NVG model. The over-predicted cases are greatly improved. The under-predicted cases (I) are not so improved because the NVG point is generated at a higher subcooling temperature in small hydraulic diameter, therefore, the bubble generation rate need to be increased by modifying the wall evaporation model. The result of the pipe experiment (II) is deteriorated as the original model is suitable for the OFI prediction in a pipe.

3.2. Improvement of the wall evaporation model

As already mentioned, the wall evaporation model need to be modified to increase the bubble generation rate in a channel with a small hydraulic diameter. Figure 2 also suggests that bubble generation rate should be increased in a high heat flux condition. The term F_{Gam} has significant role in predicting the axial void fraction. Eq. (8) shows that the original F_{Gam} did not consider the effect of the hydraulic diameter and heat flux. Therefore, we proposed a modification to the wall evaporation model as follows:

$$F_{Gam} = \min\begin{pmatrix} 1.0, 0.0022 + 0.11M - 0.59M^2 + 8.68M^3 \\ -11.29M^4 + 4.25M^5 + 0.8121\left(df^{0.513} qf^{0.34}\right)\sin(\pi M) \end{pmatrix}, \quad (12)$$

where $df = \max\left(1.0, \frac{0.0035}{D_h}\right) - 1$ and $qf = \max\left(1.0, \frac{q''}{3\times 10^6}\right)$.

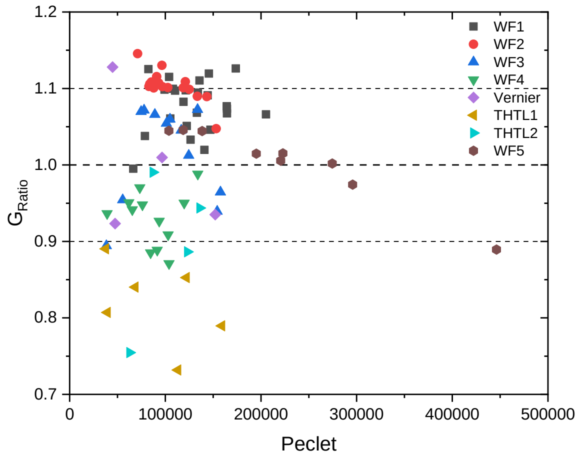
4. Assessment of the modified model

The modified subcooled boiling model is implemented to the MARS code and assessed with the same experimental database. The modified model also assessed against a set of void fraction experiment in a rectangular channel to ensure that the modified model doesn't deteriorate the original void fraction prediction.

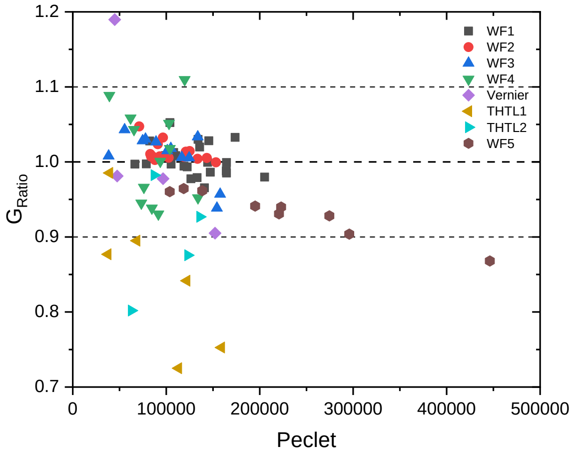
Figure 6 shows the comparison between the original and the modified subcooled boiling model. The under-predicted case such as the W-F 4 experiment managed to be improved. However, the OFI prediction for THTL 1 and THTL 2 are only slightly improved. It shows the limitation of the modified model as it unable to significantly improve the OFI prediction in a channel with hydraulic diameter less than 2.5 mm. Nevertheless, the OFI prediction is greatly improved as shown in Table 3. The modified model greatly reduces the MAPE of the OFI prediction in a rectangular channel by 53.14 %.

Table 3. Quantitative evaluation between the original and modified model.

Model	MAPE	
	All Experiment	Rectangular Channel
The original	8.22 %	8.77 %
The modified	4.37 %	4.11 %
Reduction of the MAPE	46.84 %	53.14 %



(a) The original model



(b) The modified model

Figure 6. Comparison of the OFI prediction.

Quantitative evaluation for the void fraction prediction is provided in Table 4. The void fraction error (ε) is defined as:

$$\varepsilon = \frac{1}{N}\sum_{i=1}^{N}\left|\alpha_{Experiment,i} - \alpha_{MARS,i}\right|, \quad (13)$$

where $\alpha_{Experiment,i}$ is the experiment void fraction at location i and $\alpha_{MARS,i}$ is the MARS void fraction at location i.

Table 4. Quantitative evaluation for the void fraction prediction.

Experiment	Test No.	Data Points	Average void fraction error	
			The original	The modified
Christensen [16]	7	112	0.0330	0.0322
Cook [17]	61	1066	0.0382	0.0380
Marchatterre [18]	24	430	0.0210	0.0212
Marchatterre [19]	141	1337	0.0490	0.0428
Total	233	2945	0.0404	0.0375
Reduction of the $\varepsilon_{average}$			7.18 %	

Based on the data shown in Table 4, it can be said that the modified model managed to improve the void fraction prediction.

5. Conclusions

We have assessed the MARS code for the prediction of OFI using a total of 87 OFI experiments. It was shown that the MARS code failed to predict the OFI in a rectangular channel well as it did not consider the effect of the hydraulic diameter and heat flux in a rectangular channel. Therefore, we propose a modification to the subcooled boiling model as it is directly related to the OFI phenomena. We introduced correction factors considering the effect of the hydraulic diameter and heat flux. The modified model is then compared to the original model. It was shown that the modified model can better predict the OFI mass flux in a narrow rectangular channel. Furthermore, the modified model also improves the prediction of the void fraction in a narrow rectangular channel.

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