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An empirical correlation for the onset of flow instability in narrow vertical rectangular channels

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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.

For a research reactor with plate type fuels, OFI is one of the significant indicators for the design and safety analysis. If the OFI occurs, the flow rate suddenly decreases, which can lead to abrupt damage of the fuel due to the occurrence of the critical heat flux (CHF). Therefore, it is necessary to design so that OFI does not occur under operating and transient conditions.

The correlations presented by Whittle-Forgan [2] and Saha-Zuber [3] have been widely used for the prediction of OFI. The NVG correlation of Saha-Zuber is a representative correlation, which predicts the point where the bubbles generated are rapidly increasing. The NVG model could be used as a conservative indicator for the OFI. Recently, Ha et al. [4] proposed a new NVG correlation, which better predicts than the Saha-Zuber NVG correlation. The model is outstanding, especially at low-pressure conditions. The new NVG model can also be used for the prediction of OFI.

In this study, various OFI experimental database has been collected and, then, an empirical correlation is proposed for the prediction of OFI. Finally, the empirical correlation has been evaluated against the various experimental DB compared to the existing OFI correlations and, the results are discussed.

2. Onset of flow instability

2.1 Phenomenology

Flow instability is usually classified in static or dynamic instability [5]. The Ledinegg instability, also called the flow excursion, is a static instability which cause a rapid decrease of the mass flow rate in a heated channel. The instability occurs when the pressure drop – mass flux curve for the external supply system becomes greater than that for the internal channel demand:

$$\left.\frac{\partial \Delta p}{\partial \mathrm{G}}\right|_{Supply} \geq \left.\frac{\partial \Delta p}{\partial \mathrm{G}}\right|_{Dem\,and} \tag{1}$$

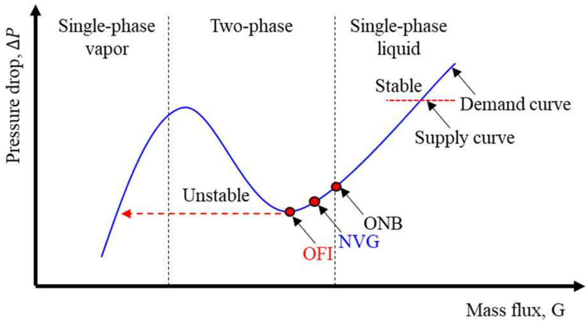

Fig. 1. The onset of flow instability for a heated channel.

As shown in Fig. 1, the demand curve (blue line), which is known as S- or flow redistribution curve) for a heated channel and, the slope of the supply curve (red line) is zero. In the channel, the operative condition corresponds to the intersection between the demand and the supply curves.

In the single-phase liquid region, the mass flux is high and the system is stable, because the slope of demand curve is greater than that of the supply curve. When the mass flux becomes lower, the channel reaches ONB point, where bubble starts to be generated on the heated surface. When considering further reducing the mass flux, the channel reaches NVG point, where bubbles are rapidly generated. After that, the channel reaches the OFI point which satisfy Eq. (1) and, a flow redistribution occurs because the only possible stable operating point is on the single-phase vapor region, where the slope of demand curve is positive. The flow redistribution instability could trigger the premature occurrence of CHF. Because of the mechanism of OFI occurrence, the NVG correlation could be used as a conservative indicator.

2.1 OFI correlations

The correlations presented by Whittle-Forgan [2] and Saha-Zuber [3] have been widely used for the prediction of OFI. Ha et al. [4] proposed a new NVG model which better predicts than the Saha-Zuber NVG correlation, especially at low-pressure conditions. The correlations are summarized in Table 1.

Table 1. The correlations for the prediction of OFI.

Authors	Formula of correlation
W-F [2]	$\mathrm{St} = 0.01$
S-Z [3]	$\mathrm{St} = \begin{cases} \frac{455}{Pe} \; for \;\; Pe \le 70{,}000, \\ 0.0065 \; for \;\; Pe > 70{,}000. \end{cases}$
Ha et al. [4]	$\mathrm{St} = \begin{cases} \frac{1}{\{Pe(0.0901 - 0.0893 exp\,(-158/Pe))\}} \; for \;\; u^* \le 1.3, \\ St \; = 0.0959 \frac{Pr^{0.58}}{Pe^{0.23}} \; for \;\; u^* > 1.3. \end{cases}$

3. An empirical OFI correlation

3.1 Collection of OFI experimental data

A total of 117 OFI experimental sets have been collected in available literature [2, 6, 7, 8]. The geometry information and T-H conditions of the experiments are summarized in Tables 2 and 3, respectively. T-H conditions of these experiments are mainly low-pressure, which include most of the operating conditions for Kijang research reactor.

3.2 Proposal of an empirical OFI correlation

Ha et al. [9] proposed a NVG model by finding the similarity between the NVG correlation and the form of an algebraic expression for the single-phase heat transfer coefficient. With reference to the algebraic expression form, we propose an empirical correlation below:

$$\mathrm{St} = \begin{cases} 0.0109 \times \frac{Pe^{0.4}}{Pr^{1.53}} \left(\frac{D_{heat}}{L_{heat}}\right)^{0.806} \;\; for \;\; Pe \le 52{,}000, \\ St \; = 0.306 \left(\frac{1}{Pe^{0.108} Pr^{0.157}}\right) \left(\frac{D_{heat}}{L_{heat}}\right)^{0.454} \;\; for \;\; Pe > 52{,}000. \end{cases} \tag{2}$$

Table 2. Geometry information of the experiments.

Exp.	No. of tests	Gap (mm)	Width (mm)	L_{heat} (mm)	L_{heat}/D_h
Up-flow experiments with uniform heat flux					
W-F No. 1 [2]	16	3.23	25.4	609.6	94.5
W-F No. 2 [2]	16	2.44	25.4	406.4	83.3
W-F No. 3 [2]	15	2.03	25.4	406.4	100
W-F4 No. 4 [2]	12	1.40	25.4	533.4	190.9
W-F No. 5 [2]	9	-	-	609.6	94.5
THTL No. 1[6]	29	1.27	13.4	507.0	195.6
THTL No. 2[6]	4	1.27	26.1	507.0	197.5
AI-Yahia and Jo [7]	6	2.35	54	300	29.55
Kim et al.[8]	3	2.35	54	300	29.55
Down-flow experiment with uniform heat flux					
W-F No. 1 [2]	7	3.23	25.4	609.6	94.5
Total	117	1.27 ~3.23	13.4 ~54	300 ~609.6	29.55 ~197.5
Kijang research reactor	-	2.35	66.6	6410	136.2

Table 3. T-H conditions of the experiments.

Exp.	$\ddot{q}$ (MW/m^2)	P_{out} (MPa)	T_{in} (℃)	G	Pe_{out}
Up-flow experiments with uniform heat flux					
W-F No. 1 [2]	0.8~2.5	0.117	35 ~60	2,222 ~5,829	67,415 ~208,207
W-F No. 2 [2]	1.23 ~2.42	0.117 ~0.172	45 ~65	2,601 ~5,637	71,936 ~156,337
W-F No. 3 [2]	0.66 ~3.0	0.117	45 ~75	1,650 ~9,204	38,741 ~215,659
W-F4 No. 4 [2]	0.67 ~2.26	0.117	35 ~65	2,405 ~8,209	39,698 ~135,536
W-F No. 5 [2]	0.86 ~3.48	0.117	45 ~65	2,619 ~11,249	105,376 ~453,076
THTL No. 1[6]	0.7~16.8	0.17 ~1.73	40 ,45	2,131 ~20,890	33,091 ~325,051
THTL No. 2[6]	2.3~6.5	1.68 ~1.73	45	3,348 ~8,057	52,366 ~129,947
AI-Yahia and Jo [7]	0.14 ~0.57	0.104~ 0.126	35 ~65	236 ~788	6,750 ~22,810
Kim et al.[8]	0.19 ~0.31	1.03	50	246 ~449	7,020 ~12,858
Down-flow experiment with uniform heat flux					
W-F No. 1 [2]	0.78 ~1.48	1.17	45 ~55	824 ~3,361	53,988 ~120,031
Total	0.14 ~16.8	0.12 ~1.73	35 ~160	151 ~20,325	6,750 ~358,460
Kijang Research reactor*	1.57	0.2	36	5,866	169,176

*Steady-State condition

4. Assessment of OFI correlations

The calculated *St* by OFI correlations were quantitatively assessed against the experimental *St* using the mean absolute error (MAE):

$$MAE = \frac{1}{n} \sum_i^n \left| \frac{St_{exp,i} - St_{cal,i}}{St_{exp,i}} \right| \times 100 \tag{3}$$

For each experiment, the averaged MAE is presented in Table 3. When comparing the NVG correlations of Saha&Zuber and Ha et al., total MAE in the Ha et al. is lower than that in S-Z model because the model is outstanding at low-pressure conditions. The experiments of AI-Yahia&Jo and Kim et al. showed considerably large MAE. The both models do not seem to predict OFI point well for the low *Pe* region (see Table 3). Nevertheless, the results from the NVG models are meaningful because it conservatively predicts OFI.

The proposed correlation shows a significantly lower total MAE than the other correlations. Especially, total MAE of the proposed correlation was reduced by about half values compared to the W-F correlation. Therefore, the proposed empirical correlation can be used for the OFI prediction, instead of the other correlations.

Table 3. MAE of OFI correlations for each experiment.

Exp.	No. of OFI data	MAE			
		S-Z	Ha et al.	W-F	The proposed correlation
Up-flow experiments with uniform heat flux					
W-F No. 1 [2]	16	38.6	12.1	6.8	7.3
W-F No. 2 [2]	16	41.1	13.2	9.3	4.6
W-F No. 3 [2]	15	31.8	11.5	4.7	6.4
W-F4 No. 4 [2]	12	19.3	26.1	25.3	12.0
W-F No. 5 [2]	9	14.7	12.4	33.0	23.8
THTL No. 1[7]	29	21.4	27.8	43.0	13.5
THTL No. 2[7]	4	53.5	51.8	44.4	43.0
AI-Yahia and Jo [8]	6	861.4	626.9	92.4	31.5
Kim et al.[9]	3	774	429	83.7	24.1
Down-flow experiment with uniform heat flux					
W-F No. 1 [2]	7	36.2	12.8	2.8	9.5
Total	117	189.2	122.4	34.5	17.6

5. Conclusions

An empirical correlation was proposed for the prediction of OFI in narrow vertical rectangular channels. The correlation was quantitatively assessed against various OFI experimental data, which include most of the operating conditions for Kijang research reactor, and compared with the assessment results with other correlations. From the assessment results, the conclusions have been drawn that the proposed empirical correlation can better predict the point of OFI than the other correlations and it can be used for the prediction of OFI in narrow vertical rectangular channels.

Nomenclature

$c_{p,f}$	liquid specific heat (J/kg·K)
St	Stanton number, $\frac{\ddot{q}}{Gc_{p,f}(T_{sat}-T_{OFI})}$
Pe	Peclet number, $\frac{GD_h c_{p,f}}{k_l}$
Pr	Prandtl number, $\frac{c_{pf}\mu}{k_f}$
D_{heat}	heated equivalent diameter
L_{heat}	heated length of flow channel
$\ddot{q}$	wall heat flux (W/m^2)
P	pressure (MPa)
T	temperature (℃)
G	mass flux (kg/m^2·s)

Subscripts

in	inlet
out	outlet
sat	saturation
OFI	onset of flow instability

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