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Improvement of the SPACE Subcooled Boiling Model for the High Pressure and Low Flow Conditions

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1. Introduction

One of the most important two-phase flow processes for thermal non-equilibrium conditions is the subcooled nucleate boiling. The prediction of void fraction in subcooled boiling region is of considerable interest for the normal operations as well as transient or accident conditions in the typical pressurized water reactor (PWR) since the void existence in the core significantly affects the response of the reactivity. According to Collier [1], the boiling flow can be broken down into three modes: single phase convection, subcooled boiling, and saturated boiling. For the single phase convection, no vapor exist and normal forced or free convection cooling tends to dominate in heated channel or pool. The subcooled boiling occurs as the wall superheating arrives at the point of the onset of nucleate boiling (ONB). The subcooled boiling can be commonly subdivided into two major parts such as high and low subcooled flow boiling regions which are distinguished by the net vapor generation (NVG) point.

In most of the best-estimate thermal-hydraulic system codes, such as RELAP5 [2] and SPACE [3], the void fraction in the heated section under the subcooled boiling conditions is predicted by several closure relations [1] based on the NVG point and the pumping factor suggested by Saha and Zuber (1974) and Bowring (1962), respectively. The RELAP5 subcooled boiling model was investigated in an extensive assessment over a wide range of pressures, flow rates, and heat fluxes [4]. On the other hand the SPACE subcooled boiling model has not been performed to verify and validate for high pressure and low flow rate conditions. In this study, the SPACE subcooled boiling model has been investigated and evaluated against the RELAP5 predictions performed by Devkin [4].

In Section 2, the comparison analysis of SPACE and RELAP5 subcooled boiling models is described in detail. Then a new subcooled model for SPACE is proposed in Section 3.The assessment results for the proposed model are presented in Section 4.

2. SPACE and RELAP5 Subcooled Boiling Models

The subcooled boiling model implemented in SPACE and RELAP5 is almost the same. The model consists of the several sub-models predicting the NVG point, the pumping factor, the interfacial condensation, and the transition criterion between bubbly and slug flow regimes. Both codes utilize the concept of the pumping factor in the subcooled boiling model suggested by Bowring [5] who took into account the bubble nucleation on the heating surface using the heat balance in association with the agitation and evaporation forces of a bubble. The most relevant closure relations in subcooled boiling model used by SPACE and RELAP5 are summarized in Tables I and II, respectively.

As shown in the tables the closure relations in the subcooled boiling model of the both codes are almost identical except for those for wall heat and mass transfer. As mentioned above, the SPACE subcooled boiling model has not been assessed for high pressure conditions. Hence, the assessment against experimental data for the high pressure conditions corresponding to the normal operations of the pressurized water reactors (PWRs) should be preferentially performed to improve the performance and reliability of SPACE. In order to perform the assessment of the SPACE code for the conditions, there is a selected Bartolomey experiment amid various evaluations performed by Devkin [4] using RELAP5. The initial and boundary conditions of that experiment are provided in Table III.

Fig. 1 shows the void fraction versus the equilibrium quality of the experimental data associated with relatively high pressure conditions and the predictions with SPACE and RELAP5. The features of the SPACE input model used herein are identical to those of RELAP5 model provided by Devkin [4]. Fig. 2 presents the comparison of the nodalization schemes for SPACE and RELAP5. From Fig. 1, it can be shown obviously that the SPACE code has some defects in predicting the subcooled flow boiling at high pressure conditions in contrast, the RELAP5 prediction shows good agreements with experimental data. Therefore the SPACE subcooled boiling model has to be improved.

3. Proposed Subcooled Boiling Model for SPACE

As already described, the prediction of the subcooled boiling region with SPACE shows bad agreements with the experimental data for high pressure conditions. From an intensive review of the subcooled boiling model, the bubble departure model used to calculate the pumping factor was suspected to be the main reason for the bad predictions, since the model was developed assuming a pool boiling condition instead of a flow boiling condition. Thus it was proposed that the bubble departure model in the SPACE subcooled boiling model should be changed to the model based on the convective flow boiling condition as follows:

- **Bubble Departure Diameter (d_b)** [6]

$$d_b = \frac{1.21 \cdot a \cdot \alpha}{\sqrt{b \cdot C \cdot \phi}} \tag{1}$$

- **Bubble Departure Frequency (f)** [7]

$$f = 0.032 \Delta T_w^{3.08} \tag{2}$$

where a, b, C, α, ϕ, and ΔT_w mean the ratio of the different heat fluxes between heated surface and subcooled fluid, ratio of the subcooling and fluid density, the pressure contribution factor for the bubble growth, the ratio of the bubble departure and average bubble diameters, the ratio of the initial and liquid bulk velocities, and the superheat of the thin liquid layer under the bubble, respectively.

4. Assessment Results

In order to evaluate the proposed model, the Bartolomey experiment simulated by Devkin [4] using RELAP5 was selected in this study. The thermal hydraulic conditions of the experiment are listed in Table III. As mentioned in Section 2, the SPACE nodalization shown in Fig. 2 is almost the same as that of RELAP5 model generated by Devkin [4]. The boundary condition was modeled using two TFBC (Temporal Flow Boundary Condition) components defining the inlet flow and the outlet pressure conditions. The test section including the heater is modeled by a pipe component and a heat structure having 15 axial nodes.

Fig. 3 compares the SPACE predictions with the current model to Bartolomey experimental data for P=~7.0 MPa and G=~1,000 kg/m^2-s at various heat fluxes q”=440~1,980 kW/m^2. A similar comparison is made in Fig. 4 for the SPACE predictions with the proposed model.

It can be seen that the proposed model can account for the effect of varied heat fluxes much better than the current model. In addition, the SPACE used in the proposed model is judged to do a reasonable task predicting the point of ONB. On the other hand, it tends to slightly over predict at the heat flux more than 1,700 kW/m^2.

5. Conclusions

In the present study, the subcooled boiling model of SPACE was compared to that of RELAP5. As a result, it was revealed that the current version of the SPACE code cannot predict well the void fraction profile in heated channel for convective subcooled flow boiling as it contains an inappropriate bubble departure model.

Thus a new bubble departure model based on the flow boiling condition was suggested in this study and the SPACE code with the proposed model can predict fairly well the Bartolomey experiment performed at relatively high pressure conditions.

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Table I. Correlations in SPACE Subcooled Boiling Model

Correlations	**Model Descriptions** [3]
Wall heat and mass transfer	• **Energy Partitioning** $q''_{ev} = \frac{q''_w}{(1+\varepsilon)} \left\{ 1 - \left[\frac{h_f^s - h_f}{h_f^s - h_{f,crit}} \right] \right\}$ Based on Lahey (1978) • **Pumping Factor** $\varepsilon = \left(\frac{2\sqrt{0.8}}{\sqrt{\pi}}\right)\left(\frac{3}{2}K\right)\frac{\rho_f}{\rho_g}\frac{\sqrt{k_f}}{\sqrt{\rho_f c_{pf} f} \cdot d_{bw}}\frac{c_{pf}(T_w - T_f)}{(h_g^s - h_f)}F$ Based on Koncar (2003) • **Bubble Departure Diameter(d_{bw})** $d_{bw} = 2.64 \times 10^{-5}\theta\left(\frac{\sigma_f}{g\Delta\rho}\right)^{0.5}\left(\frac{\Delta\rho}{\rho_g}\right)^{0.9}$ Based on Kocamustafaoguolari (1983) • **Bubble Departure Frequency (f)** $f = const.\left[\frac{\sigma g(\rho_L - \rho_v)}{\rho \cdot L^2}\right]^{1/4} / d_{bw}$ Based on Zuber (1963)
Point of NVG	$h_{cr} = h_{f,sat} - \frac{St' Pe^{0.124} C_{pf}}{0.0287} \quad (Pe > 52,000)$ $\quad = h_{f,sat} - \frac{St' Pe^{1.08} C_{pf}}{918.525} \quad (Pe \leq 52,000)$ Based on Ha and No (2005)
Interfacial condensation model	$H_{if} = \frac{F_3 F_5 h_{fg} \rho_g \rho_f \alpha_{bub}}{\rho_f - \rho_g}$ Based on Unal (1976)
Criterion between bubbly and slug flow	$0.3 \leq \alpha_{BS} \leq 0.51$ Based on Rouhani (1983)

Table II. Correlations in RELAP5 Subcooled Boiling Model

Correlations	**Model Descriptions** [2]
Wall heat and mass transfer	• **Energy Partitioning** The same as SPACE Model (see Table I). • **Pumping Factor** $\varepsilon = \frac{\rho_f\left[h_f^s - min\left(h_f, h_f^s\right)\right]}{\rho_g h_{fg}}$ Based on Rouhani (1970)
Point of NVG	$h_{cr} = h_{f,sat} - \frac{St' C_{pf}}{0.0065} \quad (Pe > 70,000)$ $\quad = h_{f,sat} - \frac{Nu' C_{pf}}{455} \quad (Pe \leq 70,000)$ Based on Saha and Zuber (1974)
Interfacial condensation model	The same as SPACE Model (see Table I). Based on Unal (1976)
Criterion between bubbly and slug flow	$0.001 \leq \alpha_{BS} \leq 0.5$ Based on Taitel (1980)

Table III. Experimental Conditions for Bartolomey [4]

Geometry	**Type**	Tube
	Hydraulic Diameter(m)	0.012
Conditions	**Heat Flux (kW/m^2)**	420~2,210
	Pressure (MPa)	3.0~14.99
	Mass Flux (kg/m^2-s)	405~2,024
	Subcooling (K)	11~140
Remarks		Uniform heat flux over the tube surface

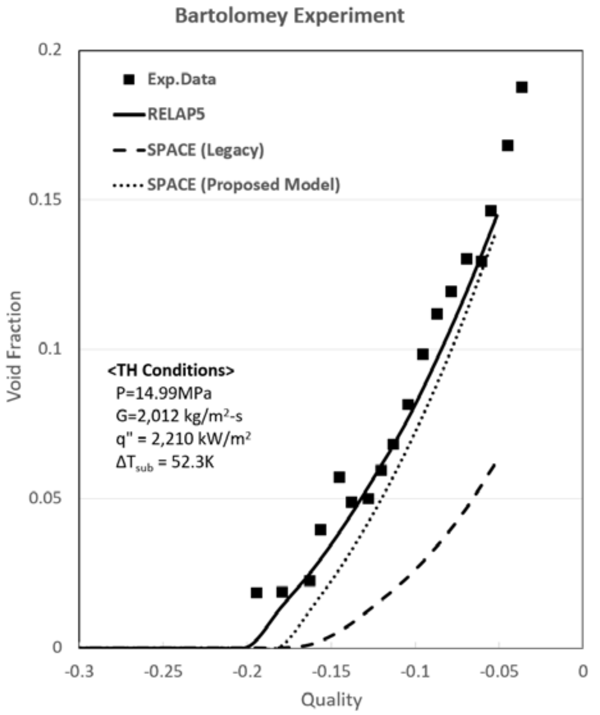

Fig. 1. Comparison of SPACE and RELAP5 Predictions with Bartolomey Experimental data

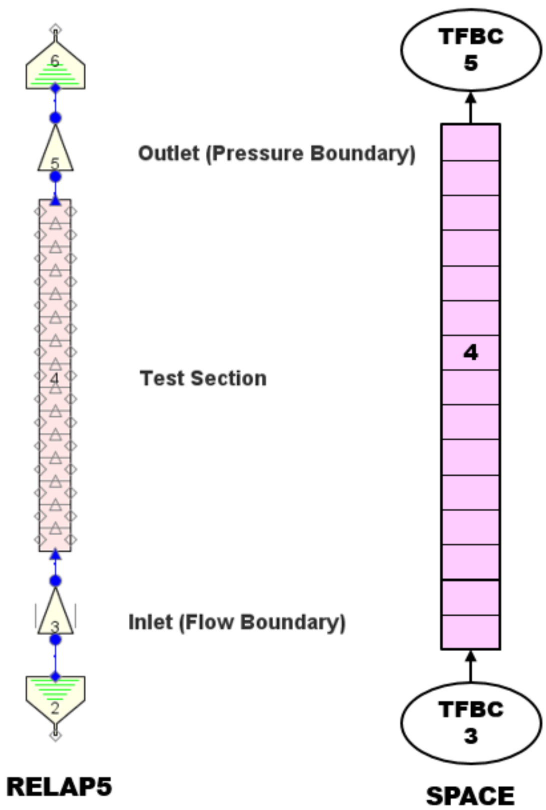

Fig. 2. SPACE and RELAP5 Noding diagrams for the Assessment of the Subcooled Boiling Experiment

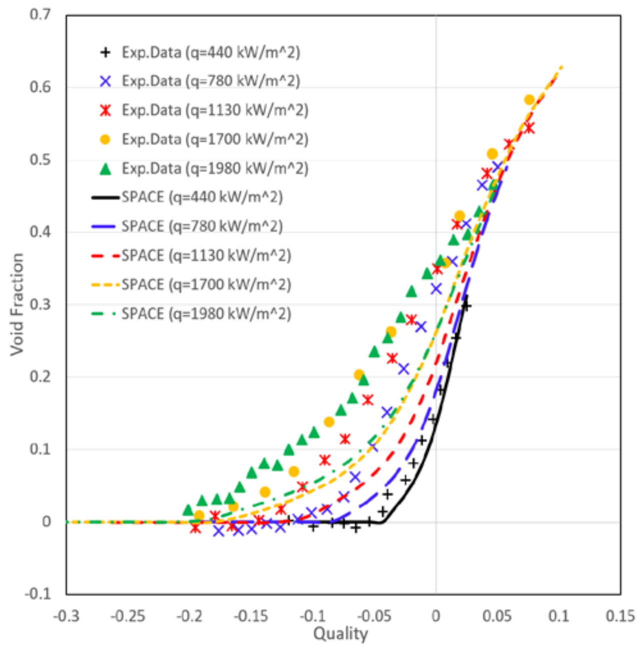

Fig. 3. Comparison of SPACE Predictions using Legacy Subcooled Boiling Model with Bartolomey Experimental data

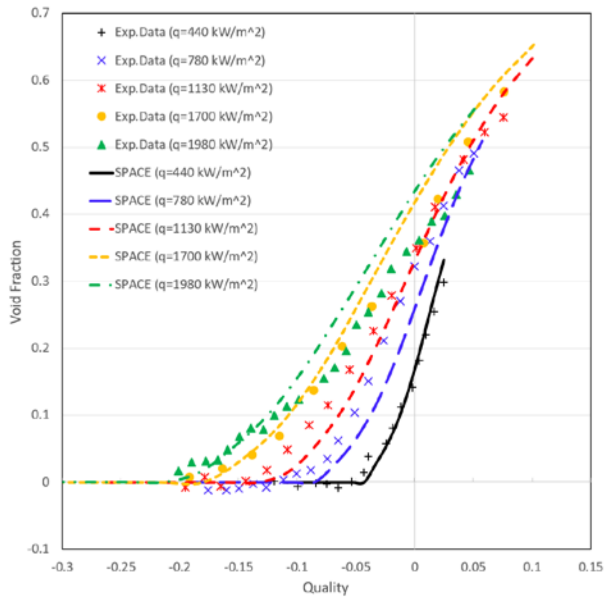

Fig. 4. Comparison of SPACE Predictions using Proposed Subcooled Boiling Model with Bartolomey Experimental data