Development of stability maps for flashing-induced instability in a passive containment cooling system for iPOWER

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Article history:
Received 14 March 2019
Received in revised form 13 June 2019
Accepted 27 June 2019
Available online 27 June 2019

A R T I C L E   I N F O
Article type: Original Article
Keywords:
Flashing-induced instability
MARS code
Stability map
Stability boundary

A B S T R A C T
A passive containment cooling system (PCCS) has been developed as advanced safety feature for innovative power reactor (iPOWER). Passive systems are inherently less stable than active systems and the PCCS encountered the flashing-induced instability previously identified. The objective of this study is to develop stability maps for flashing-induced instability using MARS (Multi-dimensional Analysis of Reactor Safety) code. Firstly, we conducted a series of sensitivity analysis to see the effects of time step size, nodalization, and alternative MARS user options on the onset of flashing-induced instability. The riser nodalization strongly affects the prediction of flashing in a long riser of the PCCS, while time step size and alternative user options do not. Based on the sensitivity analysis, a standard input and an analysis methodology were set up to develop the stability maps of PCCS. We found out that the calculated equilibrium quality at the exit of the riser as a stability boundary above 5 kW/m² was approximately 1.2%, which was in good agreement with Furuya’s results. However, in case of a very low heat flux condition, the onset of instability occurred at the lower equilibrium quality. In addition, it was confirmed that inlet throttling reduces the unstable region.

1. Introduction

The Fukushima accident highlighted the importance of containment integrity following accident condition with extended loss of AC power (ELAP) due to a large-scale natural disaster. For post-Fukushima actions, nuclear regulatory bodies and industries have established safety enhancements for operating nuclear power plants (NPPs) to ensure key safety functions following extreme unanticipated events. The safety enhancements can be achieved through portable and diverse equipment, increasing unanticipated events. The safety enhancements can be achieved through portable and diverse equipment, increasing emergency preparedness.

For new NPPs designs, a passive containment cooling system (PCCS) has been developed as an advanced safety feature since the early 1990s. The advanced Passive 1000 (AP1000) PCCS design [1] has a steel containment vessel that provides a heat transfer surface between the containment system and the atmosphere. During an accident, water falls down to the outer surface of the steel containment vessel by gravity so that heat is transferred from the containment to the atmosphere. The economic simplified boiling water reactor (ESBWR) PCCS [2] has passive heat exchangers located in a large pool. Following a postulate accident, a mixture of steam and non-condensable gas in the containment flows into the heat exchanger and condensation occurs inside heat exchanger tubes, via which the containment heat is transferred to a large pool. The innovative power reactor (iPOWER) [3], vodo vodyanoi energetichesky reactor-1200 (VVER-1200) [4] and Hualong pressurized reactor 1000 (HPR1000) [5] have passive heat exchangers installed inside the containment vessel and a large water pool as a ultimate heat sink located in the outside of the containment. After accidents such as a large-break loss-of-coolant accident (LBLOCA) and a main steam line break accident (MSLB), condensation occurs at the outer surface of the heat exchangers and the water temperature inside the heat exchanger tubes increases. The resulting difference in water density between the tubes and the large pool induces natural circulation flow in the system removing heat from the containment vessel.

These passive safety systems have advantages over conventional
active ones. In general, the driving force of the passive system is gravity causing natural circulation without any pumps, AC power, and a component cooling system. Therefore, the design of the safety system can be simplified, which could reduce plant cost. A disadvantage of passive safety system is that driving force is relatively low compared to active safety system. This low driving force can lead to instability problems. Instability is a common problem for both the active and the passive systems, but the passive system is inherently less stable than the active system [6].

The instability of the PCCS for iPPOWER was first reported by Lim et al. [7]. They noted that a phase change mechanism of this system was flashing, which induced the flow instability in the long riser pipe; however, detailed analysis of the instability was not undertaken. Flashing-induced instability (FII) was first observed in an open natural circulation test loop by Wissler et al. [8]. Since then, many researchers performed experimental studies of the FII under the low pressure of natural circulation system [9–12]. They focused on instability problems in ESBWR during startup. Furuya et al. [9] performed FII tests at the SIRIUS-N facility to investigate the instability mechanism for ESBWR, and then develop a stability map. The authors developed a stability map expressed in the non-dimensional subcooling number ($N_{sub}$), which is the fraction of the sensible liquid enthalpy of the inlet and the latent heat of vaporization, and heat flux plane, and suggested that a stability boundary was approximately 1.1% of equilibrium quality at the riser vaporization, and heat flux.

The authors developed a stability map expressed in the non-dimensional subcooling number ($N_{sub}$), which is the fraction of the sensible liquid enthalpy of the inlet and the latent heat of vaporization, and heat flux plane, and suggested that a stability boundary was approximately 1.1% of equilibrium quality at the riser exit. Manera et al. [10] conducted FII tests with multiple heating channels at the CIRCUS test facility. They pointed out that flashing was the main reason for instability, where increasing the system pressure stabilizes the instability and reduces the unstable region. The stability map was presented in a subcooling degree-heating power plane. Marcel et al. [11,12] performed similar tests using the same facility with a single heating channel and two parallel ones, which showed different oscillation behavior. They observed that an increase in the inlet restriction reduced the unstable region plotted in $N_{sub}$-phase change number ($N_{pc}$) plane. Apart from the studies by Furuya et al., a specific stability boundary has not been proposed [10–12]. Table 1 summarizes the experimental conditions used in previous studies and the expected operating conditions of PCCS in iPPOWER. The experimental conditions in the previous studies can cover the expected operating conditions of PCCS, however, the PCCS has a very long riser pipe and the heating channel, and a large number of the heating channels compared to the test facilities used in the previous studies.

Since the late 1980s, several researchers have analyzed the FII using numerical methods. Manera et al. [13] conducted an extensive literature review of FII. Several studies [14,15] failed to predict FII in the startup of BWR using TRACG code (a time domain code with two-fluid model). In contrast, Andersen et al. [16] simulated the SIRIUS-N test facility and reproduced qualitative behavior of the FII using TRACG code; however, the amplitude of the oscillation was under-predicted, and the unstable region at low power was not predicted. A simplified code based on a homogenous equilibrium model (HEM) was used by several researchers. Sawai et al. [17], Inada et al. [18], and van Bragt et al. [19] developed time-domain code or frequency-domain code using HEM. These simple codes could not accurately reproduce the stability boundary and the non-linear effects compared to experimental data. Manera et al. [13] analyzed CIRCUS test results using 4-equation two-phase model FLOCAL code, which well predicted the onset of instability, the oscillation period, and the onset of two-phase stable flow. However, the maximum flow rate of the oscillation was over-predicted since the steam dome, which affects feedback behavior, was not included in the simulations.

Over the last decades, various groups have tried to validate safety analysis codes for the FII phenomenon. Tiselj and Cerne [20] pointed out that very small time step result in pressure oscillations and a failure of the simulation in some cases, such as very fast transients related to pressure shock waves, water hammering etc. They also noted that very small time steps lead to more accurate integration of the source term in some cases, where there exists the stiffness of the interphase exchange source terms in extremely large, such as flashing and rapid condensation; hence, careful sensitivity studies of the time step are necessary. Kozmenkov et al. [21] and Phung et al. [22] validated RELAP5 code against CIRCUS test data. The global trend of test data was reproduced well, including the riser temperature, period of flow oscillation, and pressure, while discrepancies were still observed for high-frequency unstable cases.

Fullmer et al. [23] conducted extensive validation of RELAP5 models and correlations for subcooled boiling, flashing, and condensation using a test database [24]. Relevant RELAP5 models and correlations were analyzed through comparing the default model to alternative user options: the point of net vapor generation model (PNVG); an artificial ceiling model for condensation interfacial heat transfer coefficient in subcooled boiling; a new wall condensation model; and an interfacial heat transfer model for wall vapor generation. In particular, intermittent oscillation consists of a combination of boiling and flashing at a specific test condition, so that the two models can affect the oscillation pattern. The void fraction profile along the axial position was predicted well for the boiling-dominant test cases. In case of the flashing-dominant test at low pressure, RELAP5 underestimated the void fraction profile in the non-heating zone for both default and alternative PNVG models. The author discussed that flashing was a downstream phenomenon that can be affected by upstream phenomena, such as boiling and condensation. In particular, all three phenomena interrelated among them in the test facility, so it was difficult to isolate errors related to a single phenomenon. The reference test facility seems to be unsuitable to be utilized for validating only the flashing phenomenon occurring in a long riser at low pressure and power.

Recently, Wang et al. [25] analyzed FII test results from another experimental study [26] using RELAP5 code. The test data was classified according to four oscillation modes: Intermittent and periodical oscillation; Double-peak oscillation; Sinusoidal oscillation; and Irregular but periodical oscillation. The test data represented by the above four oscillations modes were analyzed with default RELAP5 code user options. The frequencies of the intermittent oscillation and the double peak oscillation were well captured, although the maximum amplitude of flow rate oscillation

### Table 1

<table>
<thead>
<tr>
<th></th>
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</tr>
</thead>
<tbody>
<tr>
<td>Avg. heat flux [kW/m²]</td>
<td>7–150</td>
<td>0–10</td>
<td>0–20</td>
<td>0–20</td>
</tr>
<tr>
<td>Reservoir pressure [MPa]</td>
<td>0.1–0.5</td>
<td>0.1–0.5</td>
<td>0.1–0.5</td>
<td>0.1</td>
</tr>
<tr>
<td>Riser vertical height [m]</td>
<td>5.7</td>
<td>3.0</td>
<td>3.0</td>
<td>15.6</td>
</tr>
<tr>
<td>Heated channel height [m]</td>
<td>1.7</td>
<td>1.95</td>
<td>1.95</td>
<td>6.0</td>
</tr>
<tr>
<td>Number of heated channel</td>
<td>2</td>
<td>4</td>
<td>1 or 2</td>
<td>2688 per train</td>
</tr>
</tbody>
</table>
was slightly overestimated. In case of the sinusoidal oscillation, the frequency and the amplitude of oscillation were reproduced well, although the small time lag of the test data was not captured. The amplitude of the irregular oscillation was slightly underestimated. In general, RELAP5 seems to predict the FII well, even the case of irregular oscillation due to a complex combination of boiling, flashing, and condensation.

Although RELAP5 code can qualitatively predict the FII well, but the quantitative performance is still lacking. Hence, the realistic modeling, careful sensitivity analysis of the relevant models, correlations, and time step size are necessary for better prediction. Jeong et al. [27] developed MARS (Multi-dimensional Analysis of Reactor Safety) code for a multi-dimensional and multi-purpose realistic system analysis of light water reactor. The MARS code was developed through consolidating and reconstructing RELAP5 and COBRA-TF code. In the MARS code, the structure of the RELAP5 code provides versatile and robust features based on a one-dimensional two-fluid model for two-phase flow, while the COBRA-TF code provides a three-dimensional feature based on three-dimensional two-fluid and three-field models for two-phase flow.

In this study, the MARS analysis model for the PCCS was established considering real plant design data, which reflected the unique characteristics of the natural circulation system in PCCS. A series of sensitivity studies give us insight for the nodalization scheme, selections of relevant models, and correlations to better predict the FII. Stability maps for PCCS were developed using MARS code with various conditions. Based on the stability maps, a criterion for the onset of the FII was first proposed for PCCS in iPOWER, and design considerations for minimizing the FII were suggested to improve the design of the PCCS for further application. Section 1 addresses a background of this study and literature reviews related with the FII based on experimental and numerical studies. Section 2 introduces a detail analysis methodology and an analysis procedure with a description of used models and correlations in MARS code. Section 3 provides analysis results and discussions for the flashing-induced instability using various plots and representative non-dimensional numbers. Section 4 summarizes a conclusion of this study and future works.

2. Analysis methodology

2.1. Design of PCCS

As illustrated in Fig. 1, iPOWER adopted vertical heat exchangers installed inside the containment. Two large water pools, called passive containment cooling tanks (PCCTs), are located at the top of the auxiliary building. The inlet pipe provides a flow path from the bottom of PCCT to the bottom of PCCS heat exchangers (PCHXs). The riser pipe connects the PCCT and the top of the PCHXs. The outlet of the riser pipe is installed just below the initial water level of PCCT. The outlets are installed in the top of the PCHXs, and provide steam venting paths from the PCCT to atmosphere. The outlets area of the PCCT are large enough to maintain the PCCT pressure as atmospheric pressure. Preliminary design parameters of the PCCS in iPOWER were addressed by Lee et al. [3]. Recently, some design parameters were modified, as shown in Table 2. The number of tubes in the system was increased and the piping layout from the PCCTs to the PCCS heat exchangers (PCHXs) was determined.

Lim et al. [7], studied preliminary heat removal performance for the PCCS in iPOWER. After the initiation of LBLOCA, most of the containment heat is removed by passive heat sinks (PHSs) in the early period of the accident. After 2000 s, the heat removal rate of the PCCS was larger than that of the PHSs and the containment heat removal occurred mainly via the PCCS. The initial temperature of the PCCT was 49 °C (120 °F) for a conservatism and the water temperature in the PCCT increases starting from its top and later up to its bottom after the accident initiation. After 20,000 s, the temperature at the inlet of the PCHXs started to increase.

Considering FII, we can separate the heat flux range for the PCCS into two ones. Before 20,000 s, the calculated average heat flux range in the PCHXs was 10–20 kW/m², although there was no increase in the inlet temperature in the PCHXs. During this period, the FII did not occur as the inlet flow of the PCHXs still had a high degree of subcooling. After 20,000 s, the degree of subcooling in the inlet flow started to decrease, and the temperature of the riser section reached the flashing point after a certain period of time. As described in Table 2, the heat flux range of interest was 2–10 kW/m².

2.2. Analysis procedure

Fig. 2 shows a flow diagram of the procedure used in this study. The first step was base input generation where one train of the PCCS was modeled as a base input for a series of sensitivity analysis. To obtain a preliminary stability map of the PCCS, the major system variables were modeled as boundary conditions and initial conditions, such as system flow rate, ultimate heat sink temperature (PCCT temperature), heat flux into the PCHXs, and initial water temperature of the loop. Using a base input, base analyses were conducted by varying the boundary flow rate, the boundary temperature, and the initial loop temperature at a fixed heat flux condition. The base analysis results can be converted into a stability map plotted in the Npsw-Npct plane. From the preliminary stability map, the resulting system flow rate was classified according to the oscillation pattern; then representative cases were selected for further sensitivity analysis.

The second step was a series of sensitivity analyses. Previous
The bundle header was quite long but modeled using one branch component with a single junction as 336 PCHX tubes in each bundle were modeled as a single lumped channel. The unit volume of the bundle header was set to be \( L / D_h = 1.3 \).

The hydrodynamic volume of one PCHX bundle was modeled with twelve vertical volumes using a pipe component. The volume and flow area were the same as those of the 336 tubes in one bundle. The hydraulic diameter in the volumes and internal junctions was the same as a single tube diameter. The junction connecting the bundle header volume and PCHX volume applied the flow loss coefficient, which was calculated by a typical engineering handbook. One train of the PCCS had eight PCHX bundles connected in parallel with the distributor header, as shown in Fig. 3. The unit volume was set to be \( L / D_h = 19.46 \). This value was significantly larger than the other models, so nodalization sensitivity was performed for the PCHX model.

To simulate the heat transfer into the hydrodynamic volumes, the solid part of the tubes was modeled with twelve vertical heat structures and five points in the radial meshes. The twelve axial heat structures were connected to the twelve hydrodynamic volumes of the PCHX. A convective boundary condition was used for the left side of the heat structure, while a heat-flux boundary condition using a general table was used for the right side. All hydrodynamic volumes had adiabatic conditions, except for the PCHX hydrodynamic volumes.

The riser pipe is important for simulating the flashing phenomenon. Sensitivity analysis of the rise nodalization was performed to evaluate the node size effect. The riser pipe was modeled using pipe and valve components. As for the inlet pipe modeling, the real piping layout information was completely conserved, where the unit volumes was set to be \( L / D_h = 3.1 \). In reality, the outlet of the riser pipe is connected into the top of the water volume in the PCCT. When an accident occurs, the heated water flows into the PCCT due to the natural circulation flow. Thus the temperature of the PCCT is continuously increased which means that instability patterns is continuously changed by increasing the inlet temperature. Therefore, we disconnected the outlet of riser pipe from the PCCT volume to maintain steady-state condition given a specific temperature, flow rate and heat flux.

The abrupt area change model was applied to internally calculate the flow loss coefficient. In the base and sensitivity analysis, the system inlet flow rate and the inlet temperature were controlled by the time-dependent volume (TMDPVOL) and junction (TMDPJUN) connected to the top of the PCCT model. The TMDPVOL was always in the single-phase liquid state. The TMDPVOL was under the atmospheric pressure, while the temperature is varied from 48.8 °C to 99 °C. The system outlet boundary condition was modeled using the TMDPVOL, which set the atmospheric pressure, the room temperature, and air only state.

2.4. MARS analysis matrix and user options

Following the described analysis procedure, the MARS analysis matrix shown in Table 3 was established. First, the base analysis was conducted to obtain a preliminary stability map and select the representative oscillation patterns. The heat flux was fixed to 5 kW/m² as the FLI was observed under this heat flux condition in the previous study [7]. The base nodalization and default user options were used in this analysis, and the time step was 0.05 s. In both the base analysis and a series of sensitivity analysis used a fixed inlet flow rate and inlet temperature for maintaining a steady state condition.

In the first step of the sensitivity analysis, the nodalizations for the riser and the PCHXs were refined to evaluate the effect of node size and the parallel channel effect. In the second step of the
Table 3
MARS analysis matrix.

<table>
<thead>
<tr>
<th>Subjects</th>
<th>Nodalization</th>
<th>Time step [s]</th>
<th>Inlet boundary condition (Flow rate and Temperature)</th>
<th>Heat flux [kW/m²]</th>
<th>User options</th>
</tr>
</thead>
<tbody>
<tr>
<td>Base analysis Sensitivity analysis</td>
<td>Base</td>
<td>0.05</td>
<td>d</td>
<td>5</td>
<td>Default</td>
</tr>
<tr>
<td>- Nodalization</td>
<td>Base</td>
<td>0.05</td>
<td>c</td>
<td>5</td>
<td>Default</td>
</tr>
<tr>
<td></td>
<td>Base</td>
<td>0.05</td>
<td>c</td>
<td>5</td>
<td>Default</td>
</tr>
<tr>
<td></td>
<td>Fine(Riser)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Fine(PCHX)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Parallel channel</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>- Time step</td>
<td>a</td>
<td>0.05, 0.01, 0.002</td>
<td>c</td>
<td>5</td>
<td>Default</td>
</tr>
<tr>
<td>- User options</td>
<td>a</td>
<td>b</td>
<td>c</td>
<td>5</td>
<td>Default, 20, 24, 37, 65</td>
</tr>
<tr>
<td>Development of Stability Map</td>
<td>a</td>
<td>b</td>
<td>d</td>
<td>10, 5, 3.5, 2</td>
<td>e</td>
</tr>
</tbody>
</table>

a: Determined from nodalization sensitivity analysis; b: Determined from time step sensitivity analysis; c: Fixed values determined from selected conditions; d: Full range of inlet flow rates and temperatures; e: Determined from user options sensitivity analysis.
sensitivity analysis, the time step size was varied (0.05, 0.01, and 0.002 s). The third step was comparing user options to the default MARS models. Fullmer et al. [23] well addressed detail models and correlations of RELAP5 user options related with the FII, as shown in Table 4. Option 24 activates the original RELAP5 subcooled boiling model. The default model is more suitable for low pressure condition [28]. Option 37 deactivates the umbrella model, which provides an upper limit for the liquid interfacial heat transfer coefficient in the default model when the liquid is subcooled. Option 65 provides an additional option for the subcooled boiling and applies only the nucleate boiling heat flux into the wall vapor generation. This can minimize the repetitive activation and deactivation of subcooled boiling model in low pressure and low flow conditions. In this study, Option 20 was used as one of the sensitivity items, which enables a smooth bubbly-slug transition region and minimize artificial oscillation when the flow regime is frequently changed from bubbly and slug flow.

3. Analysis results and discussion

In this section, MARS code analysis results are discussed. In this study, the stability map is plotted in $N_{\text{sub}}$-$N_{\text{pch}}$ plane. The subcooling number and the phase change number are defined as:

$$ N_{\text{sub}} = \frac{h_f - h_{in}}{h_{fg}} \times \frac{\rho_f - \rho_g}{\rho_g} \quad (1) $$

$$ N_{\text{pch}} = \frac{Q}{Wh_{fg}} \times \frac{\rho_f - \rho_g}{\rho_g} \quad (2) $$

where $h_f$ is the saturated liquid enthalpy, $h_{in}$ is the specific enthalpy at inlet, $h_{fg}$ is the latent heat of vaporization, $\rho_f$ is the saturated liquid density, $\rho_g$ is the saturated vapor density, $Q$ is the heating power, $W$ is the system flow rate. The stability boundary can be expressed in terms of equilibrium quality, $x_{eq}$ in the $N_{\text{sub}}$-$N_{\text{pch}}$ plane. Furuya et al. [9] defined $x_{eq}$ at the riser exit:

$$ x_{eq, \text{riser}} = \frac{h_{ch, \text{out}} - h_f \text{ex.riser}}{h_{fg, \text{ex.riser}} - h_f \text{ex.riser}} = \frac{h_{in} + Q/W - h_f \text{ex.riser}}{h_{fg, \text{ex.riser}}} \quad (3) $$

where $h_{ch, \text{out}}$ is the specific enthalpy at the outlet of heating channel. Using Eq. (3), the relationship between $x_{eq}$ and the two non-dimensional number is:

$$ Wh_{fg, \text{ex.riser}} x_{eq, \text{ex.riser}} = W \left( h_{in} - h_f \text{ex.riser} \right) + Q \quad (4) $$

Eq. (4) can be express as follows:

$$ Q_{\text{pch}} = -Q_{\text{sub}} + Q \quad (5) $$

Using Eqs. (1)–(3), we obtain Eq. (6):

$$ 1 - \frac{N_{\text{sub}}}{N_{\text{pch}}} = 1 - \frac{Q_{\text{pch}}}{Q} = \frac{Wh_{fg, \text{ex.riser}} x_{eq, \text{ex.riser}}}{Q} \quad (6) $$

Therefore, the definition of $N_{\text{sub}}$ and $N_{\text{pch}}$ can be rewritten by:

$$ N_{\text{sub}} = \frac{h_f \text{ex.riser} - h_{in}}{h_{fg, \text{ex.riser}}} \times \frac{\rho_f \text{ex.riser} - \rho_g \text{ex.riser}}{\rho_g \text{ex.riser}} \quad (7) $$

$$ N_{\text{pch}} = \frac{Q}{Wh_{fg, \text{ex.riser}}} \times \frac{\rho_f \text{ex.riser} - \rho_g \text{ex.riser}}{\rho_g \text{ex.riser}} \quad (8) $$

3.1. Base analysis results

Oscillation patterns for the FII have been classified in various studies in different way. Furuya et al. [9] defined intermittent periodic and sinusoidal oscillations and Marena et al. [10], defined

<table>
<thead>
<tr>
<th>Subjects</th>
<th>Default models</th>
<th>Models for User options</th>
</tr>
</thead>
<tbody>
<tr>
<td>Option 24: Point of net vapor generation and wall heat transfer</td>
<td>$h_{f, \text{ex}} = h_f - C_{pu} \frac{Nu}{455}$ (Pe ≤ 70,000)</td>
<td>$h_{f, \text{ex}} = h_f - C_{pu} \frac{St}{455}$ (Pe &gt; 70,000)</td>
</tr>
<tr>
<td></td>
<td>$h_{f, \text{cr}} = h_f - \frac{0.0055}{0.00055}$</td>
<td>$h_{f, \text{cr}} = h_f - \frac{0.0055}{0.00055}$</td>
</tr>
<tr>
<td>Mul</td>
<td>$h_f + f_{\text{ps}}(P_{\text{ps}} - h_f)$</td>
<td>$h_f + f_{\text{ps}}(P_{\text{ps}} - h_f)$</td>
</tr>
<tr>
<td></td>
<td>$H_{f,b} = a_{\text{sf}}, \text{max}$</td>
<td>$H_{f,b} = a_{\text{sf}}, \text{max}$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$H_{f,b} = \frac{f_{\text{ps}}h_{fg} \rho_f \phi_{\text{ps}}}{\max(1, \Delta T_{\text{sub}})} \left(D_b^2 \right)$ \quad (Te &lt; T^\circ)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$H_{f,b} = \min \left{ 3.2 \times 10^5 \Delta T_{\text{sub}}, \frac{2.2 \times 10^4 \phi_{\text{ps}}}{10^4} \right}$ \quad (Te &gt; T^\circ)</td>
</tr>
<tr>
<td>Option 65: Wall heat transfer</td>
<td>$h_{f, \text{ex}} = h_f \frac{A_w}{\max(h_{bg}, 10^4 \text{Mul})}$</td>
<td>$h_{f, \text{ex}} = h_f \frac{A_w}{\max(h_{bg}, 10^4 \text{Mul})}$</td>
</tr>
<tr>
<td></td>
<td>$h_f + f_{\text{ps}}(P_{\text{ps}} - h_f)$</td>
<td>$h_f + f_{\text{ps}}(P_{\text{ps}} - h_f)$</td>
</tr>
<tr>
<td></td>
<td>$\text{Mul} = \frac{h_f + f_{\text{ps}}}{1.0 + (P_{\text{ps}}(h_f - h_{\text{in}}))}$</td>
<td>$\text{Mul} = \frac{h_f + f_{\text{ps}}}{1.0 + (P_{\text{ps}}(h_f - h_{\text{in}}))}$</td>
</tr>
</tbody>
</table>

| Table 4 | Comparison between default models and user options [23,29]. |
similar two patterns, intermittent natural circulation and unstable two-phase natural circulation. Marcel et al. [12] classified the oscillations into three patterns: In-phase oscillation (same with intermittent oscillation); a-periodical oscillations; and out-of-phase oscillation (same with sinusoidal oscillation and similar to a-periodical oscillations). Wang et al. [25] classified four oscillation patterns: intermittent and periodical oscillation; double-peak oscillation; sinusoidal oscillation; and irregular but periodical oscillation.

Considering the aforementioned experimental studies, the common unique characteristics of intermittent oscillation was a delay time (incubation time) between the occurrence of flashing to the next one [11]. When the flashing in the riser section is vigorous, the system flow rate sharply increases causing the sudden suppression of the flashing. Then, the system flow rate becomes stagnant for quite a long time until the temperature increases the boiling point of the fluid in the heating channel or the flashing point in the riser section. In contrast, sinusoidal oscillation has no incubation time. Wang et al. [25] classified four oscillations based on the oscillation patterns being dependent on a combination of subcooled boiling, saturated boiling, geysering, and condensation with flashing. The three other oscillations, except for the intermittent oscillation, can be classified as sinusoidal oscillation since they have no incubation time. Here, we classified only two oscillation patterns, sinusoidal oscillation and intermittent oscillation.

Fig. 4 shows the preliminary stability map and the stability boundary determined from the base analysis. Each point plotted in the \( N_{\text{sub}} - N_{\text{pch}} \) plane is the result of a single calculation using a certain inlet flow rate and inlet temperature. The single calculation were performed during 6000 s and the variables of interest were averaged over 5000–6000 s. In some cases, the analysis time is extended to 20,000 s to achieve a steady state. The inaccessible region means that the inlet flow rate is lower than zero which is a non-physical condition. The colored solid lines represented a theoretical \( x_{\text{eq}} \) ones at the exit of the riser calculated by using Eqs. (3), (7) and (8). Furuya et al. [9] noted that \( x_{\text{eq}} \) was required to be higher than 1.1% for the FIL. From the base analysis, we obtained the stability boundary as shown in Fig. 4, where the stability boundary was 1.17% (calculated using the minimum exit quality) or 1.31% (using the average exit quality). The results were in good agreement with the experimental data [9].

Fig. 5 shows the oscillation patterns for selected cases. As shown in Fig. 5(a) and (c), it is difficult to identify whether these oscillations were sinusoidal oscillation or not, while Fig. 5(b) definitely shows intermittent oscillation and Fig. 5(e) shows sinusoidal oscillation. As Fig. 5(a) and (c) showed short incubation times, they were classified as intermittent oscillation. Among the intermittent oscillation, various patterns were observed depending on the inlet subcooling degree and inlet flow rate. Representative cases from the base analysis were selected, as labeled (a) to (i) in Fig. 4, which were used for further sensitivity analyses.

Fig. 6(e) shows the sinusoidal oscillation patterns for the temperatures and sum of vapor generation in the system, which represents point (e). This point is the onset of the FII. The cooling water was heated, but boiling did not occur in the heated tubes as the water still had the subcooling margin due to the hydrostatic head in the heated tubes. When the heated water flows into the long riser section, flashing occurs at the riser exit due to a loss of static head. This flashing results in an increase of the natural circulation flow rate so that lower temperature of the water flows into the riser section, thus flashing decreased slightly in the riser section. Finally, the natural circulation flow rate becomes low and the exit temperature of the heated tubes increases again. The repetition of this process results in sinusoidal behavior in the natural circulation loop.

Fig. 6(f) shows the intermittent oscillation patterns for the temperatures and sum of vapor generation in the system, which represents point (f). This point was apart from the stability boundary, as shown in Fig. 4(a). The oscillation mechanism was similar to that of the sinusoidal oscillation, however, in this case, the vapor generation was larger than the sinusoidal case because the natural circulation flow rate sharply increased and the tube outlet temperature suddenly decreased below the saturation temperature suppressing the flashing. During the incubation time, boiling occurred in the tubes firstly and flashing occurred in the riser section secondly. This pattern of the vapor generation induced the typical intermittent oscillation pattern.

3.2. Sensitivity analysis results

The first step in the sensitivity analysis was to study the nodal sensitivity, which was performed in two cases. We first evaluated the riser nodalization sensitivity as the riser model is important for simulating the flashing phenomenon. The nodes of the riser were refined from \( L/D_h = 3.1 \) to \( L/D_h = 1.5 \). The second case was the PCHX nodalization sensitivity, which was studied through refining the nodes of PCHXs from \( L/D_h = 19.5 \) to \( L/D_h = 9.7 \): boiling of the water in the PCHXs can affect the intermittent oscillation patterns.
during the incubation time. In the second case, the refined riser model was also applied. The third case was the parallel channel sensitivity. The one bundle of PCHS had 336 of tubes and the single channel represented the one bundle of PCHX in the base model. The base model had 8 channels for the single train of PCCS. For third case, the 8 channels of PCHX were divided into 16 channels with the refined riser model.

After nodalization refinement, the amplitude and period of oscillation slightly changed but there are no significant differences apart from the points (g) and (h), which showed a smaller degree of subcooling than that in the other cases, as shown in Fig. 7. In the base analysis, the points (g) and (h) were defined as intermittent oscillation. After nodalization refinement, point (g) become stable and point (h) showed sinusoidal oscillations. In the system analysis code, scalar properties such as pressure, energy, and void fraction of flow were defined at the cell center. The coarse nodes in the riser section may induce lower hydrostatic pressure than the fine nodes may do. The case with coarse nodes had a higher vaporization rate in the riser section than that with fine nodes, which leads to the difference between the base node case and riser node refinement cases. In addition, there were no significant differences between the riser refinement case and the PCHX refinement case, as shown in Fig. 7. For the parallel channel effect, 16 channels model showed no significant effect for the oscillation pattern of FII in Fig. 7. The frequency and amplitude of oscillation in 16 channels model were almost same with the 8 channels model with refined riser model. In conclusion, we confirmed that the coarse modeling of the riser section induced artificial oscillations and modeling with fine nodes is preferred for minimizing artificial oscillations.

The second step in the sensitivity analysis was to study the sensitivity of time step through varying the maximum time step by 0.05, 0.01, and 0.002 s. As shown in Fig. 8, the results of the sensitivity analysis showed no significant effect of the time step on the oscillation patterns, although the amplitude of the oscillation and the frequency of the oscillation slightly changed in some points of the representative cases. Tiselj et al. [20] noted that the RELAP5 code well captured the steep gradient for quasi-second-order pressure waves when a small time step is used, although the numerical oscillations appeared. Hence, we determined a maximum time step size of 0.05 s.

The third step in the sensitivity analysis was to study the
dependency of the user options. Fig. 9 shows selected points (e), (f), and (h), which were most affected by the user options.

The option 37 affected the sinusoidal oscillation, where point (h) changed from sinusoidal oscillation to an almost stable state. In case of intermittent oscillation, the amplitude and frequency of the oscillations changed slightly, but there was no significant effect. This option deactivates an artificial limitation in the liquid interfacial heat transfer coefficient, as shown in Table 4. In the MARS code, the interfacial heat and mass transfer was calculated as:

$$
\Gamma_{ig} = \left[ \frac{H_{ig}(T^* - T_g) \left( \frac{P_s}{P_f} \right) + H_{ig} \left( T^* - T_f \right)}{h^*_g - h^*_f} \right] \quad (9)
$$

where \( H_{ig} \) is the liquid interfacial heat transfer coefficient, \( H_{ig} \) is the liquid interfacial heat transfer coefficient, \( T^* \) is the saturation temperature, \( T_g \) is the gas temperature, \( T_f \) is the liquid temperature, \( P_s \) is the saturation pressure, and \( h^*_g \) and \( h^*_f \) are the phasic enthalpies. For flashing, \( h^*_g = h_g \) and \( h^*_f = h_f \). In general, the umbrella model is helpful to prevent extreme liquid interfacial heat transfer coefficient in the case that the void fraction approaches 0.0 or 1.0 [30]. Hence, the deactivation of the umbrella model can result in the overestimation or underestimation of the vapor generation in the riser section. Consequently, the default and alternative models of MARS code can reflect consistent oscillation patterns except for options 37, and the use of the option 37 is not recommended.

3.3. Development of stability maps

The standard inputs determined from the sensitivity analysis were as follows: standard nodalization for the riser refinement case; time step of 0.05 s; and default models and correlations in the MARS code were used. In this section, we discuss the development of the stability maps through varying the heat flux boundary conditions, which are consistent with those expected in the LBLOCA situation.

Fig. 10 shows the stability maps for each heat flux condition, where the stability characteristic for each condition were qualitatively similar with each other. When the exit quality of the riser section exceeded approximately 1.0%, the stable flow became unstable. In most of the unstable region, the intermittent oscillation was dominant. The sinusoidal oscillation appeared between the stable and the intermittent oscillation, and the sinusoidal oscillation was observed only at a very low subcooling degree in the 10 kW/m² case. In the 2 kW/m² case, the sinusoidal oscillation region enlarged with a higher subcooling degree since the heat flux in the heating channel was not sufficient to stimulate the change from the sinusoidal to intermittent oscillation. In the experimental studies, intermittent oscillations were observed in higher subcooling regions at the atmospheric pressure condition, while sinusoidal oscillations were rarely observed in the very lower
subcooling region between intermittent oscillation region and two-phase stable region [9,10]. In addition, the sinusoidal oscillation were dominant instead of the intermittent oscillation when the system pressure increased as flashing is suppressed. Marcel et al. [11,12], obtained different experimental results. The large area of the sinusoidal oscillations appeared in the stability map. Therefore, the difference of those system characteristics such as the different riser length and unique loop pressure drop characteristics might induce the difference in the distribution of the oscillation patterns in the unstable region.

Fig. 11(a) shows the stability boundaries at each subcooling and heat flux condition, and Fig. 11(b) presents the minimum stability boundaries at each heat flux condition. The minimum stability boundary was defined as a minimum value among the calculated equilibrium equalities of the onset of FII in each heat flux condition. Above 5 kW/m², the calculated equilibrium quality at the exit of the riser as a stability boundary was approximately 1.2%, which were good agreement with Furuya’s results [9], as shown in Fig. 11(a). Below 3.5 kW/m², the minimum stability boundary was less than 1.0% of the quality. In particular, the system operating condition easily moved into the unstable region for a higher subcooling degree and low heat flux condition.

To further compare with Furuya’s data, the 15 kW/m² and 20 kW/m² cases were analyzed. As shown in Fig. 11(b), MARS code well captures the minimum of stability boundary when the heat flux is larger than 5 kW/m², while the minimum of stability boundary sharply decreased below 5 kW/m².

In summary, the stability maps reflecting the detail system information of the PCCS were obtained using MARS code. The stability maps of the PCCS were qualitatively similar with several experimental results. In particular, the calculated equilibrium quality of the riser exit as a stability boundary is good agreement with those from the previous experimental studies. To support this analysis results, further experimental study may be necessary, which should consider characteristics of natural circulation system for the PCCS.

It is well known that an increase in the inlet restriction can reduce the unstable region. As shown in Fig. 12, the inlet throttling effect was analyzed through using the input and analysis methodology described in the previous section. When the inlet restriction increased, the equilibrium quality of the exit riser increased slightly for the case of higher subcooling condition. In case of the
low subcooling degree, the inlet throttling had a large effect, and the stable region was much wider than that without it. The inlet throttling has a positive effect on system stability since the inlet restriction increases single-phase flow friction and provides a damping effect on the system flow [11,31,32]. However, it also has a negative effect on the heat removal performance of the PCCS as the inlet restriction reduces the natural circulation flow rate in the system following an accident condition.

4. Conclusions

The MARS analysis model has been established to predict FII in PCCS. Sensitivity analysis was performed to see the effects of the nodalization scheme, and provided insights for selection of time
step size, and alternative models and correlations in MARS code for better prediction of FII. Coarse nodalization of the riser section induced artificial flashing oscillations and fine nodes is preferred to estimate accurate vapor generation in the riser section. The oscillation patterns is not much sensitive to the selection of the time step size, but marginally sensitive to alternative user options in MARS code. Hence, use of the typical time step size and the default MARS models are acceptable for predicting the FII in PCCS.

Fig. 10. Stability maps for various heat flux conditions: (a) 10 kW/m², (b) 5 kW/m², (c) 3.5 kW/m², and (d) 2 kW/m².

Fig. 11. (a) The stability boundaries at each subcooling number and (b) the minimum stability boundaries at each heat flux condition.
Based on the standard input and the analysis methodology, the stability maps for the PCCS were developed for further design optimization. We found out that the calculated equilibrium quality at the exit of the riser as a stability boundary above 5 kW/m² was approximately 1.2%, which was in good agreement with Furuya’s results. However, in a very low heat flux condition, the onset of the FII occurred at the lower equilibrium quality than the experimental data. In addition, it was confirmed that inlet throttling reduces the unstable region, however, the design of the inlet restrictor for minimizing FII should be carefully determined through considering its negative effect on the heat removal performance.

In this paper, we mainly focus on the development of the stability map in steady-state heat flux conditions on the PCCS tube wall. We need to further study how the transient wall heat flux condition affects the stability map through coupling between containment environment and the tube wall of the PCCS for real accident transient. Also, we need a further experimental study considering unique characteristics of PCCS in order to confirm the oscillation patterns of FII and stability maps for PCCS.

Conflicts of interest

All authors have no conflicts of interest to declare.

Acknowledgements

This work was supported by the Nuclear Power Core Technology Development Program of the Korea Institute of Energy Technology Evaluation (KETEP), and granted financial resources by the Ministry of Trade, Industry and Energy, Republic of Korea (number 20161510400120).

References

Nomenclature

\( a_i \): Interfacial area (1/m)
\( A \): Surface area (m^2)
\( C_p \): Specific heat (J/kg-K)
\( d \): Diameter (m)
\( D_h \): Hydraulic Diameter (m)
\( F \): Function coefficient (–)
\( h \): Specific enthalpy (J/kg)
\( h_f \): Latent heat of vaporization (J/kg)
\( H \): Volumetric interfacial heat transfer coefficient (J/kg-K)
\( k \): Thermal conductivity (W/m-K)
\( L \): Length of volume (m)
\( M_{ef} \): Evaporation multiplier (–)
\( N_{ph} \): Phase change number (–)
\( N_{sub} \): Subcooling number (–)
\( N_{us} \): Nusselt number (–)
\( P \): Pressure (Pa)
\( Pe \): Peclet number (–)
\( Pr \): Prandtl number (–)
\( q_w \): Wall heat flux (W/m^2)
\( Q \): Heating power (W)
\( Re \): Reynolds number (–)
\( Sf \): Stanton number (–)
\( T \): Temperature (oK)
\( V \): Volume of node (m^3)
\( W \): Mass flow rate (kg/s)

Greek

\( \alpha \): Void fraction (–)
\( I \): Mass transfer per unit volume (kg/m^3-s)
\( \Delta T_{sat} \): Liquid superheat degree (K)
\( \Delta T_{sub} \): Liquid subcooling degree (K)
\( \epsilon \): Pumping factor (–)
\( \rho \): Density (kg/m^3)

Subscripts

\( b \): Bubbly flow regime
\( ch \): Heating channel
\( crit \): Critical
\( eq \): Equilibrium condition
\( ex \): Exit condition
\( f \): Liquid condition
\( g \): Vapor condition
\( i \): Interface
\( in \): Inlet condition
\( nb \): Nucleate boiling
\( out \): Outlet condition
\( pch \): Phase change
\( riser \): Riser
\( s \): Saturation condition
\( sub \): Subcooling

Superscripts

\( s \): Saturation condition