INSTABILITIES IN A PASSIVE MODERATOR COOLING SYSTEM OF SCWR-CANDU

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Abstract

This paper presents the results from the examination of instability mechanisms in a Passive Moderator Cooling System of a SCWR (SuperCritical Water-cooled Reactor) - CANDU®. Such a passive system is being developed at AECL using a flashing-driven natural circulation loop. Unstable intermittent and sinusoidal oscillations were identified from available data of the flashing-driven natural circulation in a passive moderator cooling system. The oscillation periods were correlated with the boiling delay time. A stability map was established from available natural circulation test data in the Calandria Subcooling-Power plane, and depicted boundaries between the stable and unstable areas.

1. Introduction

A Passive Moderator Cooling System for the SCWR-CANDU, using a flashing-driven natural circulation loop, is being developed at AECL [1, 2]. This passive design focuses on maintaining the role of the moderator as a passive heat sink during normal operation and improving its availability in the unlikely event of an accident involving loss of coolant combined with loss of emergency cooling. In the SCWR-CANDU design, the moderator operates slightly subcooled, which creates a condition where two-phase flow can be generated by flashing as the flow rises from the calandria, providing a significant buoyancy driving force for recirculation (see Figure 1). This driving force makes it possible to remove moderator heat under both normal operation and postulated accident scenarios.

In the natural circulation moderator system, a riser is installed on the calandria to increase natural circulation flow rate. In order to achieve the reliable cooling performance, the natural circulation moderator system has to be designed and operated to avoid two-phase instability caused by adiabatic flashing, which is induced by the hydrostatic pressure decrease as the fluid flows upward. The present natural circulation system concept is operated at a low pressure of ~ 1 atm.

Flow instabilities in two-phase boiling systems have been reviewed in papers [3 - 5]. Fukuda and Kobori [6] conducted experiments under both forced and natural circulation conditions in two parallel channels to study density wave oscillations. They classified density wave oscillations into two types: Type I and Type II. Type I instability occurred at very low steam quality conditions (at low power and high inlet subcooling), while Type II occurred at relatively high power and low inlet subcooling. Their work was mainly for conventional (GenII) boiling water reactors (BWRs), under operating or accidental conditions with high pressures (~ 7MPa) although a parametric study of wider parameter ranges was also conducted. Rao *et al.* [7] performed similar work to that of Fukuda and Kobori [6], including determining the coupled neutronic and thermodynamic instabilities in a boiling channel. They found that, besides the phase-change number and Jacob number, the Froude number and the fuel-time constant (a time–scale parameter from the fuel dynamics of the reactivity and the nuclear heat generation in Ref. 7) were the parameters determining the density wave instability. Furuya *et al.* [8] studied flashing-driven oscillations in the natural circulation of simplified boiling water reactors (SBWRs) with a long riser at low pressure during the start-up operation. The oscillations were suggested to be flashing-induced density wave oscillations after observing that the oscillation periods correlated with the passing time of single-phase liquid in the chimney section.

In this study, instability mechanisms and stability maps for flashing-driven natural circulation in a passive moderator cooling system have been examined using available experimental data and the CATHENA system code [9].

2. A flashing-driven natural circulation loop

Studies of the flashing-driven natural circulation loop have been performed to investigate two-phase flow phenomena for BWR applications [8, 10 - 13]. Natural circulation cooling is a key issue for reliable core-cooling performance in BWRs. A boiling natural circulation loop with a two-phase flashing flow is being considered for the passive natural circulation cooling of the SCWR-CANDU moderator system. Figure 1 shows a schematic of a scaled down flashing-driven natural circulation loop being operated at the Chalk River Thermalhydraulic Laboratory. The test facility demonstrates the passive moderator concept, and is being used to explore relevant phenomena.

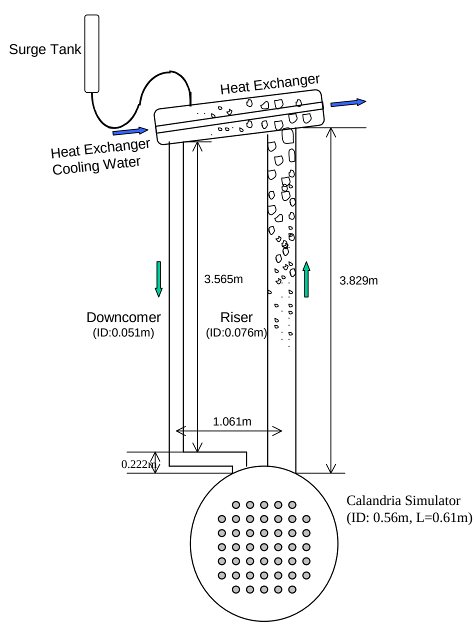

Figure 1 A schematic of the flashing-driven natural circulation loop.

The test loop consists of a simulated calandria tank, riser and downcomer, heat exchanger, and surge tank. The heat exchanger is angled to facilitate a concept of passive circulation on the secondary side. The coolant of the present heat exchanger is supplied by a forced flow with a mass-flow rate and a temperature. A surge tank is installed to capture and condense any escaping vapour from the heat exchanger. Enthalpy is added to the fluid in the heated calandria. As the fluid rises in the riser, flashing starts when the enthalpy of the fluid matches the local saturation enthalpy as the hydrostatic pressure reduces. The two-phase flashing flow condenses when it flows through the heat exchanger, resulting in a subcooled liquid that exits to the downcomer. Figure 2 shows instrumentation of the flashing-driven natural circulation loop.

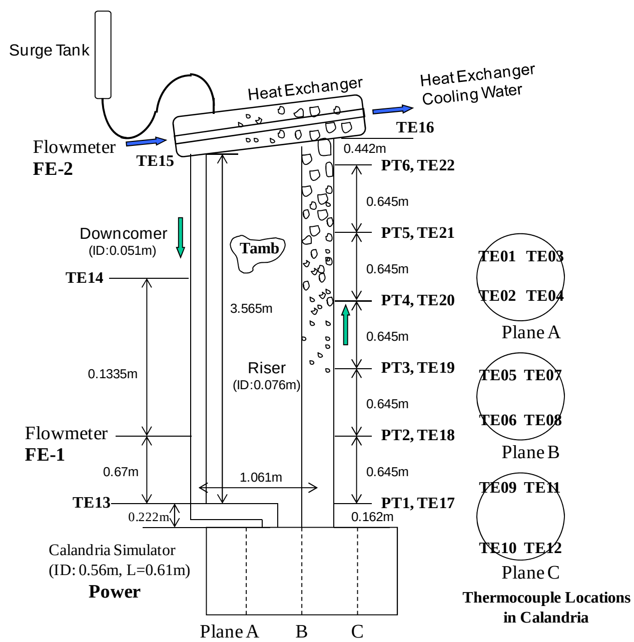

Figure 2 Instrumentation of the flashing-driven natural circulation loop. (TE01-TE22 and Tamb: thermocouples, PT1-PT6: pressure transmitters, FE-1 and -2: flowmeters)

3. Investigation of instabilities for flashing-driven natural circulation

3.1 Instability mechanisms

The importance of examining the instability mechanism in detail is to identify how to control or prevent instability in two-phase boiling channels. In general, the instabilities are suppressed as the system pressure increases [8, 14]. The instabilities can be affected by a specific flow parameter, such as flow resistance [12].

3.1.1 Unstable oscillation

Figures 3 and 4 show experimental results from the flashing-driven natural circulation tests with the test loop shown in Figure 1. In the flashing-driven natural circulation tests, four different types of behavior were observed: (a) stable at high calandria inlet subcooling or low calandria power (SH), (b) unstable intermittent two-phase flow (UIT), (c) unstable sinusoidal two-phase flow (UST), and (d) stable two-phase flow at low calandria inlet subcooling or high calandria power (SL).

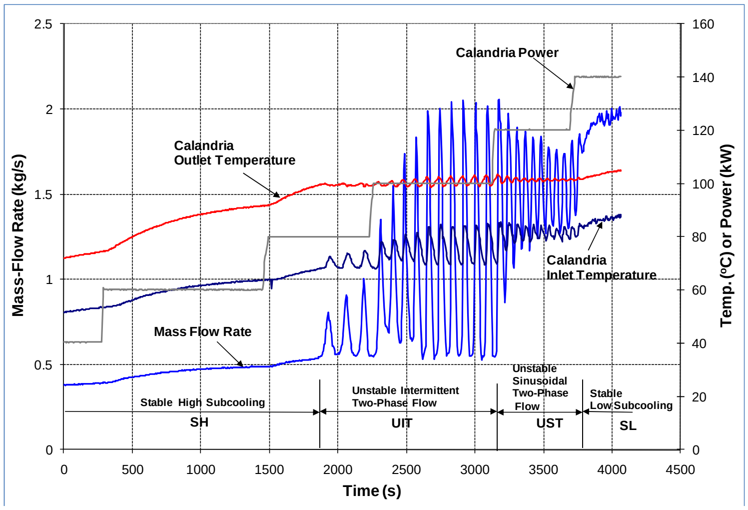

Figure 3 Experimental results: Flashing-driven natural circulation with one mode of oscillation.

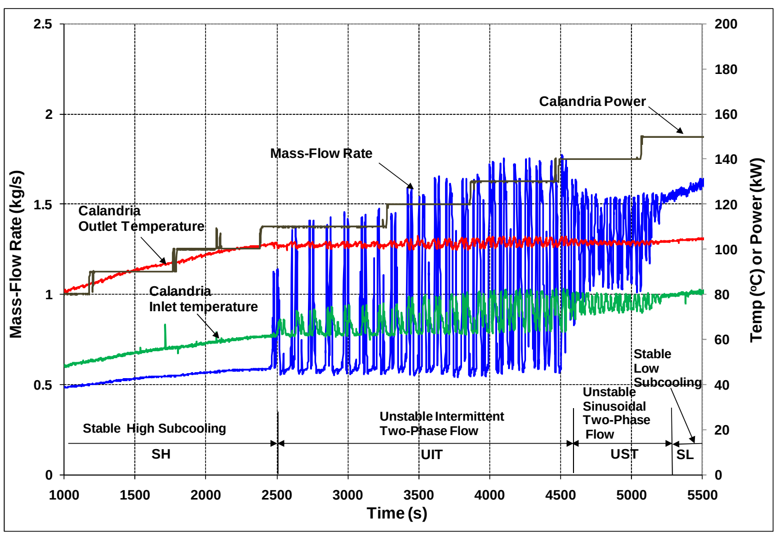

Figure 4 Experimental Results: Flashing-driven natural circulation with multiple modes of oscillation.

As can be seen in Figures 3 and 4, two types of instability waveforms are observed among the four stages of natural circulation: an intermittent oscillation at low calandria power with higher inlet subcooling and sinusoidal oscillation at high calandria power with lower inlet subcooling. The oscillation period is large at the beginning of intermittent oscillation, and decreases systematically up to the end of sinusoidal oscillation. The amplitude of oscillation increases as the intermittent oscillation develops, and decreases when the intermittent oscillation changes to the sinusoidal oscillation.

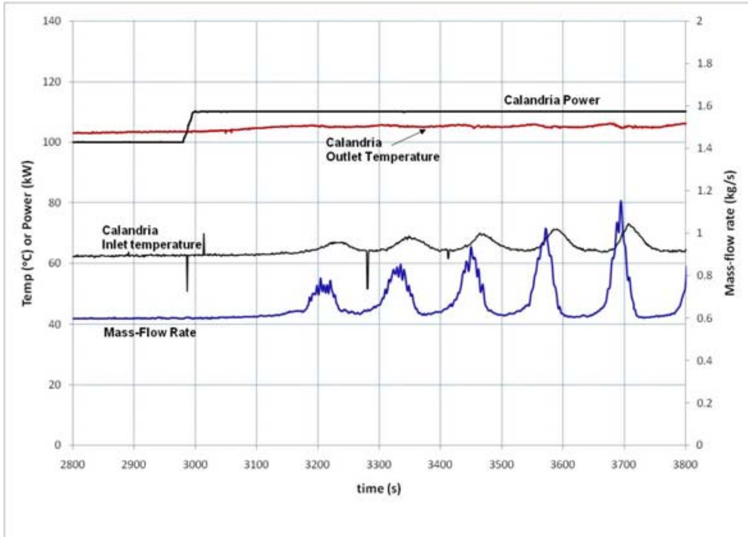

Figure 5 An example of unstable intermittent two-phase flow with one mode of oscillation.

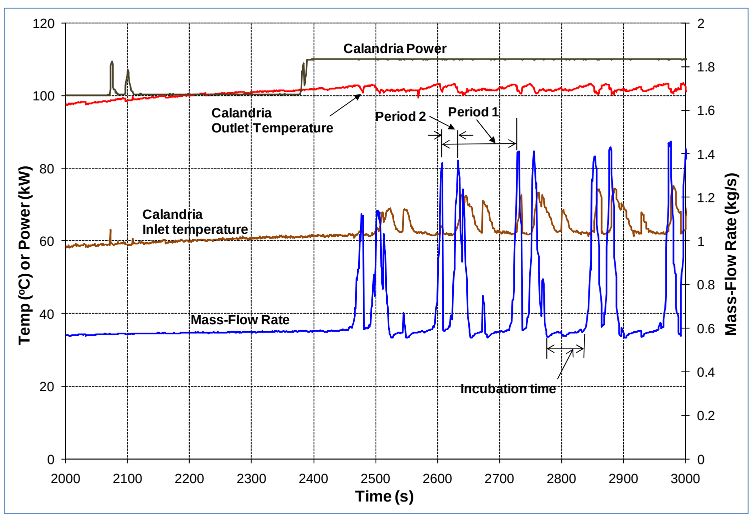

Figure 6 An example of unstable intermittent two-phase flow with multiple modes of oscillation.

Figure 5 shows a typical intermittent oscillation in which the oscillation has a single pattern in amplitude and period, or one dominant mode of oscillation. Intermittent oscillation with multiple patterns in amplitude and period, or multiple modes of oscillation, is also observed as shown in Figure 6. Period 2 in Figure 6 is shorter than Period 1, and is similar to the period of the sinusoidal oscillation shown in Figures 3 and 4. The multiple patterns in intermittent oscillation may be caused by multiple feedback mechanisms from various flow parameters. In this study, Period 1 is selected as the period characterizing the intermittent oscillation.

In the analysis of oscillation instability, the intermittent oscillation is represented by the oscillation at the beginning of the intermittent oscillation period, and the sinusoidal oscillation is represented by the oscillation at the end of the sinusoidal oscillation period. The results of the instability analysis will therefore provide the boundaries between the stable and unstable areas.

The periods of intermittent and sinusoidal oscillations of available experimental data were compared with the fluid transit time (τ_{tr}). The transit time has been evaluated as the sum of the transit time in the riser section and the transit time in the heated calandria, which is defined as

$$\tau_{tr} = \frac{V_{Riser} + V_{Heated\ calandria}}{\dot{m} / \rho} \tag{1}$$

where V_{Riser} is the volume of the riser section in m^3 and $V_{Heated\ calandria}$ is the volume of the calandria. The mass-flow rate ($\dot{m}$) in kg/s is oscillating in the intermittent and sinusoidal two-phase flows, so the mass-flow rate was averaged in the range of oscillation (time interval for the selected period). ρ is the averaged density ((riser-outlet density + calandria-inlet density)/2) between the calandria and the riser outlet in kg/m^3.

Figure 7 shows the oscillation period with respect to the fluid transit time in the riser and calandria. The oscillation period is distributed around 0.5 to 1.5 times the time required for the fluid to travel through the riser and calandria. This trend is comparable with that in Boure *et al.* [3]. Boure *et al*. [3] described that the period of density wave instabilities is approximately one to two times the time required for a fluid particle to travel through the heated channel. The present period range is below the range in the Boure *et al*.'s description.

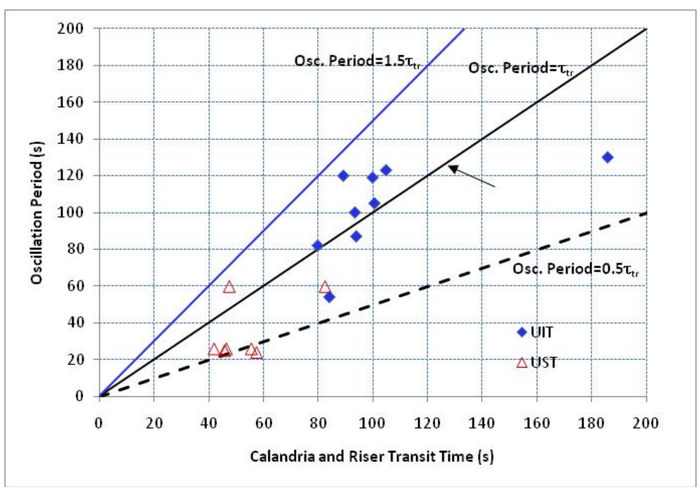

Figure 7 Oscillation period with respect to Calandria and Riser transit time (UIT: unstable intermittent two-phase flow, UST: unstable sinusoidal two-phase flow).

The periods in intermittent and sinusoidal oscillations of available experimental data were also compared with the boiling delay time. The boiling delay time is defined as the time required for the subcooled water flows to be heated up to the saturation temperature based on the pressure at the riser outlet, and can be expressed as

$$\tau_{bd} = \rho_l \left(H_f - H_l\right) / (\dot{Q} / V_{Total}) \tag{2}$$

where $\dot{Q}$ is the power of the calandria in kW, H_f is the saturated enthalpy at the riser-outlet pressure, and ρ_l and H_l are the liquid density in kg/m^3 and enthalpy in kJ/kg, respectively, at the calandria-inlet pressure and temperature. V_{Total} is the total volume of V_{Riser} and $V_{Heated\ \mathrm{Calandria}}$ in m^3.

Figure 8 shows the oscillation period with respect to the boiling delay time. The figure presents a trend that the oscillation period increases as the boiling delay time increases. The oscillation periods can be correlated with the equation

$$Osc.\,period = 0.80\tau_{bd} - 20.9 \tag{3}$$

The oscillation periods are around 25~70s lower than the boiling delay time in the range in Figure 8. The predictions (UIT-Pred, UST-Pred) using the CATHENA code in Figure 8 are discussed in the next section.

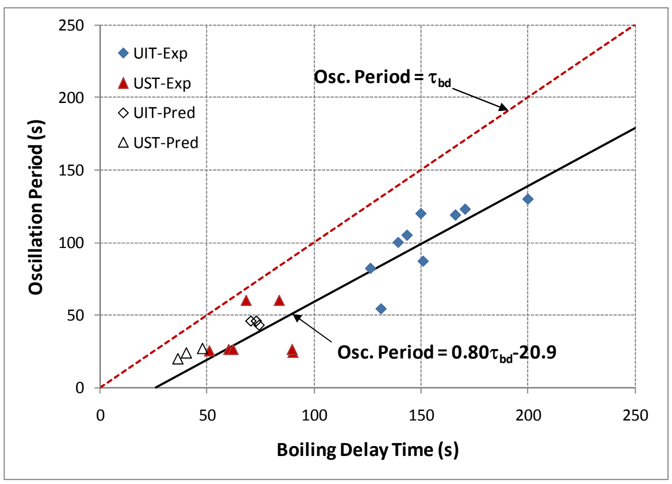

Figure 8 Oscillation period with respect to boiling delay time.

In the present passive moderator tests, the two-phase pattern was mainly a bubbly flow in the whole two-phase region of the riser. As the two-phase approached the top of the riser, it became more or less chaotic, which might be related to an oscillatory flow in the loop.

3.1.2 Prediction of oscillation with CATHENA

The oscillations for the flashing-driven natural circulation were predicted using the CATHENA code for constant calandria-inlet temperatures. A boundary condition method for CATHENA prediction, which excludes the simulation of heat exchanger and surge tank, was used in the CATHENA simulation of the natural circulation loop. Figures 9 and 10 show predictions of mass-flow rate and void-fraction oscillations at a constant calandria-inlet temperature of 70 °C. Similar to the experiment, the prediction of mass-flow rate in Figure 9 shows four different types of behaviour: (a) stable at low calandria power, (b) unstable intermittent two-phase, (c) unstable sinusoidal two-phase, and (d) stable at high calandria power. The oscillation period is maximum at the beginning of intermittent two-phase flow, and decreases systematically up to the end of sinusoidal oscillation period. The amplitude of intermittent oscillation increases in steps from the beginning of intermittent oscillation period to the starting of sinusoidal oscillation period (up to the power of 300 kW), and then the amplitude decreases to zero in sinusoidal oscillation. The trends of the period and amplitude in the prediction are similar to those of experiments.

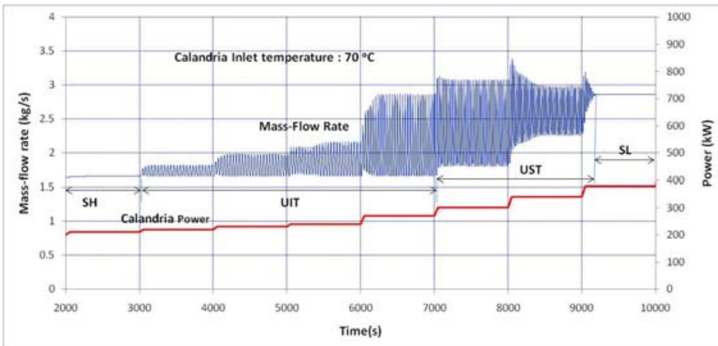

Figure 9 Predicted unstable oscillations of flow rate using CATHENA

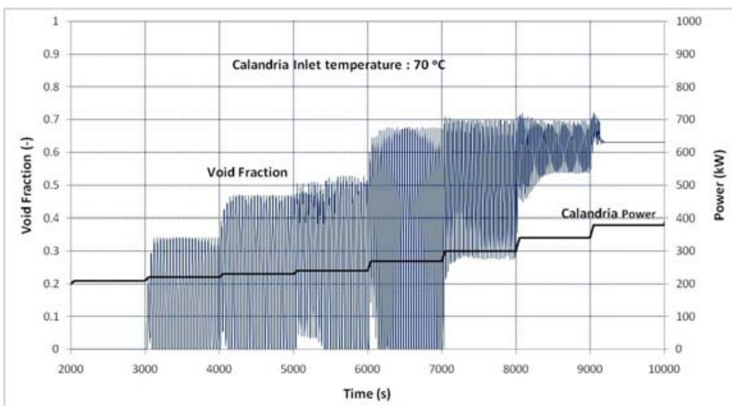

Figure 10 Predicted unstable oscillations of void fraction using CATHENA.

The void-fraction prediction in Figure 10 illustrates a boundary between the intermittent and sinusoidal oscillations. The intermittent two-phase flow can be described as a flow where two-phase flow is on and off. With this categorization, the intermittent two-phase flow continues up to the power of 270 kW. The CATHENA prediction for intermittent and sinusoidal oscillation period compared with the boiling delay time is included in Figure 8. The predicted period follows the same trend as the experimental data.

3.1.3 Categorization of instability mechanism

The instability mechanisms for flashing-driven natural circulation can be discussed based on the present observations. The flashing-driven oscillations have a feature of density wave instability. These oscillations are due to multiple regenerative feedbacks between the flow rate, vapour generation rate, and pressure drop. The present period range is around 0.5 to 1.5 times the transit time as shown in Figure 7, which indicates that the present flashing-driven oscillation is close to the density wave type of instability (1~2 times the transit time in Boure *et al.* [3] description on density wave instability). The present oscillation has a feature of Type I density wave instability [6] in the aspect of quality range. Typically Type I is defined at very low quality (low void fraction). In the present case, the quality is low, but the void fraction is very large due to the flashing at low pressure. Van der Hagen *et al*. [15] reported that the phenomenon of flashing influences Type I instability. Type I instability is dominated by gravity effects in the riser, occurring at low coolant qualities. This low-frequency phenomenon is of specific importance for the intermittent oscillation of flashing-driven natural circulation. The point is that at low pressure and low flow quality, the hydrostatic head (as imposed by the riser void fraction) is very sensitive to flow-rate fluctuations. Yang [16] suggested the Froude number as one of dominant dimensionless groups in the scaling for the flashing-driven natural circulation. The Froude number consists of parameters of mass flux, gravity, density and length. The hydrostatic head is determined by the gravity, and is related to flow-rate variation.

In the present study, the relationship between the boiling delay time and the flow oscillation period is illustrated in Figure 8. The oscillation period is lower than the boiling delay time. Also the minimum value of the flow rate in intermittent oscillation maintains the value of the single-phase at high subcooling, and thus the flow rate is large enough to prevent the formation of a water super-heated layer. Thus, the oscillation due to flashing-driven natural circulation may not fall into the category of geysering[1]. However, the oscillation having an incubation time as shown in Figure 5 can be a feature of geysering. In intermittent oscillation at the initiation of two-phase flow, the fluid is heated up maintaining the same magnitude of mass-flow rate in single-phase flow. This mechanism is similar to that of the geysering which appears in a heated liquid column with a closed bottom.

The present flashing-driven natural circulation is unique compared to other related cases [8, 10 - 13]. The heated calandria is installed at the bottom of the riser in a horizontal orientation while in other cases the heater is installed vertically connected to the riser. This uniqueness may cause some differences of instability mechanisms from other cases. Based on the observations above, the instability mechanism can be called a flashing-driven Type-I density wave instability, including a geysering-like feature in intermittent oscillation.

3.2 Stability maps

The stability map was examined with the Subcooling number-Phase Change number plane. The intermittent and sinusoidal oscillation areas were in the range of x (thermodynamic quality) =0 to x = 0.02. The thermodynamic quality is defined at the outlet of the riser. In calculating the thermodynamic quality, power comes from the calandria heat input, and the saturation property is calculated using the outlet pressure of the riser. However, some part of the single-phase stable area and the two-phase flow stable area are superimposed on the range of x =0 to 0.02 of the unstable area. The reason for the boundaries not being distinct between the stable and the

[1] Geysering has been observed in a variety of closed end (or forced flow at low flow rate) vertical columns of liquid that are heated at the base. Its process breaks down into three processes: boiling delay, condensation (or expulsion of vapour), and liquid returning [8].

unstable may be the loop operation at low pressure. In the present test loop (Figure 1), the surge tank is exposed to the ambient pressure, and the pressure at the riser outlet is ~ 1 atm. At low pressure, the void fraction increases very rapidly as the quality increases near the zero quality.

Thus, stability maps were established with the calandria inlet subcooling and power for the flashing-driven natural circulation.

Figure 11 shows the stability map for the experimental data in the calandria inlet subcooling-power plane. Some boundaries are observed between the stable and unstable areas in the experimental data. The prediction of intermittent oscillation (UIT) using the CATHENA code is included in Figure 11. The prediction is lower than the experiment, and it is in the unstable category of sinusoidal oscillation (UST). The discrepancy may be due to the simplified CATHENA simulation compared to the test facility. The boundary condition method excluded the simulation of heat exchanger and surge tank and therefore excluded feedback from these two features. This prediction using the CATHENA code is preliminary, and it may require further improvement. Figure 12 shows a preliminary stability map predicted using the CATHENA code for the extended calandria power compared to Figure 11. The figure illustrates the areas of the stable flow at high subcooling, unstable flow oscillation, and stable flow at low subcooling.

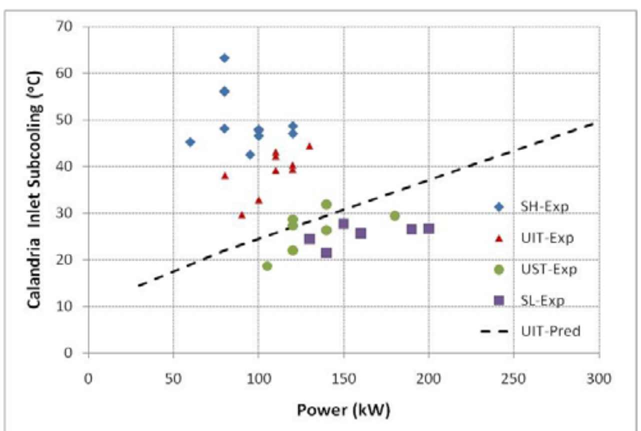

Figure 11 Stability map with Calandria power and Inlet subcooling.

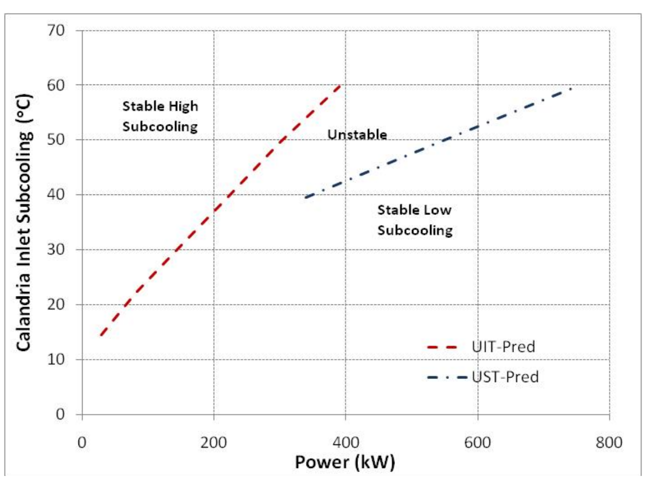

Figure 12 Preliminary stability map with Calandria power and Inlet subcooling from simplified CATHENA model.

4. Conclusions and recommendations

Instability mechanisms and stability maps for flashing-driven natural circulation in a passive moderator cooling system have been investigated using available data and the CATHENA system code. The following conclusions have been made:

- Unstable intermittent and sinusoidal oscillations were identified from available experimental data for flashing-driven natural circulation in a passive moderator cooling system. The periods of intermittent and sinusoidal oscillations were compared with the transit time (τ_{tr}), and were distributed in the range of $0.5\,\tau_{tr}$ < Osc. Period < $1.5\,\tau_{tr}$.
- A stability map was established for available experimental data from the natural circulation test in the Calandria Subcooling-Power plane, and depicted boundaries between the stable and unstable areas. The prediction of the stability map using the CATHENA code was also performed for the extended power range to show approximate boundaries between the stable and unstable areas.
- The present flashing-driven natural circulation in a passive moderator cooling system is a unique loop for the CANDU reactor, which was not investigated previously. Natural circulation loops in the literature usually consist of a vertical heated section and a riser. However, the present natural circulation loop consists of a heated calandria installed in a horizontal orientation and a riser. Based on observations using available data and related information from the literature, the present flashing-driven oscillations can be categorized as a flashing-driven Type-I density wave instability, including a geysering-like feature in intermittent oscillation. These oscillations are due to multiple regenerative feedbacks between the flow rate, vapor generation rate, and pressure drop.
- Further tests are required to confirm the instability mechanism with the test loop in which throttling and pressure can be controlled. The test results will provide information on how to control or prevent the instabilities in the flashing-driven natural circulation.

5. Acknowledgements

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6. References

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