Review of Prediction Capability of System Analysis Code for Density Wave Oscillation

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Keywords : Two-phase instability, System code, Density wave oscillation

1. Introduction

Numerous studies have been carried out over the past several decades on the two-phase flow instability [1–13]. Thermally induced two-phase instability can cause mechanical vibrations, leading to damage to the component such system. In the nuclear field, there are large component occurring two-phase flow such as Steam Generator (SG), reactor core in Boiling Water Reactor (BWR), Condenser (CD) etc. Therefore, most of researches on flow instability in the nuclear field had been focused on safety [12, 13].

Nowadays, with the development of helical coil steam generators (HCSG) applied in Small Modular Reactor (SMR), such as NuScale, Density Wave Oscillation (DWO) became an issue as the oscillation has probability to effect on SMR component [14]. To address this issue, NuScale developed an evaluation methodology on DWO demonstrating experiment [15, 16]. In addition, i-SMR is being developed with considering HCSG which is similar concept with NuScale, the similar instability seems to be occurred [17]. To validate the design and stability of helical-coiled steam generator in SMRs, it is required to assess the prediction capability of system analysis code for density wave oscillation. However, the past studies on flow instability were mainly experimental and analytical [13].

In this study, the literatures related with the prediction of DWO using system analysis code are reviewed.

2. Literature survey

The literature survey was primarily conducted on papers that investigated flow instability using system code, such as RELAP5, MARS, GOTHIC etc.

Prasad et al. [18] modeled 2-channel natural circulation loop using RELAP5/MOD3.4. The calculations were performed based on default model and lumped parameter model in RELAP5. The instability increases as the system pressure decrease or heater power increase for both cases. At the high pressure condition, the calculation results using lumped parameter model shows similar trend compared with default model.

Colombo et al. [19] performed calculations on a single channel, single channel with bypass, 2-channel and inclined 2-channel for forced convection using RELAP5/MOD3.3. The calculation results compared with Solberg [20] experimental results. The calculation results show good agree well with vertical tube, however, the results of inclined 2-channel case show difference from classical DWO theory. They reported that the further research is needed to compare with experimental research.

Zhou et al. [21] carried out experiment and calculation both on 2-channel with bypass for closed forced convective loop varying system pressure, inlet temperature, heater power and mass velocity. The calculation results of stability map coincide well with experimental results for low pressure under 7MPa. The period of instability was predicted well compared with experimental results, but amplitude is overestimated.

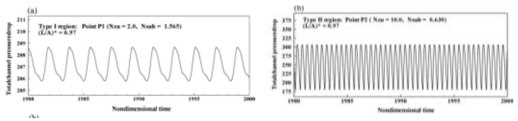
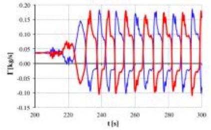
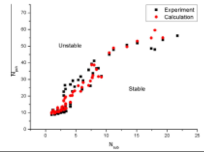
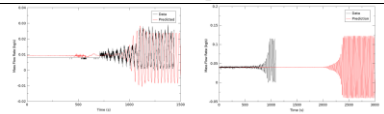
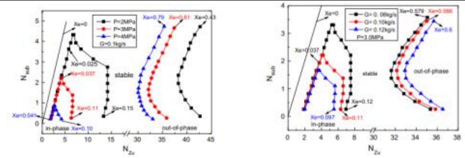
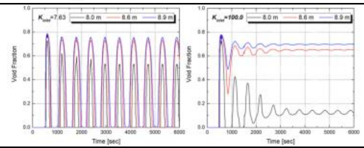
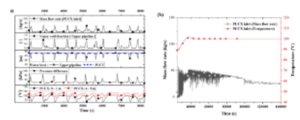
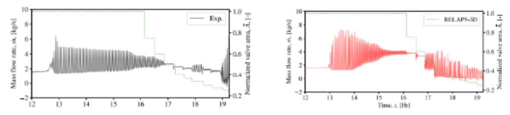
The RELAP5-3D was modified to NRELAP5 and the DWO, occurred in HCSG of NuScale, prediction was tried to evaluate the DWO characteristics. The calculation results predicted well with oscillation period and mass flow rate, but showed difference with the starting time of the onset of oscillation and amplitude [22].

Genglei et al. [23] conducted experiment and calculation using RELAP5/MOD3.3 to investigate the prediction capability of RELAP5 on DWO and flow excursion. The experiment and calculation were performed on multi-channel closed forced convection loop according to system pressure and inlet temperature. For RELAP5, equilibrium model and non-equilibrium model were applied. The number of channel varied as 2, 4 and 9. The effect of the number of channels in flow instability is negligible. The system stabilizes with increases inlet throttling, inlet subcooling, system pressure, hydraulic diameter, and decreases of heating power. They reported that more studies are needed for predicting instabilities using RELAP5, particularly regarding out-of-phase DWO caused by flow excursion, and in-phase DWO.

Kim et al. [24] carried out the calculation on 6-channel open natural circulation loop to analyze the iPower Passive Containment Cooling System(PCCS) varying with inlet temperature and heater power. The system was stabilized as the inlet loss coefficient at heater and PCCT water level increase.

Bang et al. [25] analyze the capacities of cooling system and consideration for PCCS design using

Table I: Flow instability literatures

Ref.	Instability	Used code & Geometry, T/H condition	Representative results
[18]	DWO	**Used code**: RELAP5 MOD 3.4 **Configuration**: 2-channel / closed natural circulation loop **Geometry** D_h: 0.07842 m Heater length: 3.5 m / Riser length: 5.0 m **T/H condition** P: 1.0–7.0 MPa / Q: 100–1400 kW	
[19]		**Used code**: RELAP5 MOD 3.3 **Configuration**: Forced convective Single & single with bypass & 2-channel / Forced convection **Geometry** D_h: 5.25–12.53 mm / Heater length: 2.9–3.658 m **T/H condition** P: 7.0–8.1 MPa / Inlet T: 151.3–282.3 ℃	
[21]		**Used code**: RELAP5 MOD 3.3 with experiments **Configuration**: Forced convective, 2-Channel with bypass **Geometry** 2.0 mm × 25.0 mm tube / Heater length: 1.0 m **T/H condition** P: 1.0–10.0 MPa/ Inlet T_{sub}: 20.0–50.0 ℃ q``: 0-837 kW/m^2	
[22]		**Used code**: NRELAP5 with experiments **Configuration**: Closed natural circulation loop **Geometry**: HCSG in NuScale power module (Detail data N/A)	
[23]	DWO & Flow excursion	**Used code**: RELAP5 with experiments **Configuration**: Multi-channel(2, 4, 9) closed forced convective loop **Geometry** D_h: 10 mm Heater length: 1.5 m / Riser length: 0.25 m **T/H condition** P: 1.02–3.0 MPa / Inlet T_{sub}: 154– 188 ℃ G: ~200 kg/s / Q: 23– 24.5 kW	
[24]	DWO & Flashing	**Used code**: MARS **Configuration**: 6 channel open natural circulation loop **Geometry** iPower PCCS / PCCT level: 6–16 m **T/H condition** Q: 2–8 MW / Inlet T: 50–99 ℃	
[25]	DWO & Flashing	**Used code**: GOTHIC **Configuration**: 4 channel open natural circulation loop **Geometry** Detailed data N/A **T/H condition** P: 101.3 kPa / Initial T: 48.9℃	
[26]	DWO & Flashing	**Used code**: RELAP5-3D with experiments **Configuration**: 6 channel open natural circulation loop **Geometry** D_h: 36.1 mm / Total facility height: 18.1 m **T/H condition** Q: 0–51.6kW / Detailed data N/A	

GOTHIC code. For Closed loop PCCS (CL-PCCS) case, the PCCS will be stabilized by increasing system pressure. On the other hand, Open loop PCCS (OL-PCCS), as the controlling of system pressure is impossible, the location of Passive Containment Cooling heat eXchanger (PCCX) must be carefully chosen. For both case of OL-PCCS and CL-PCCS, the system was stabilized due to the decrease of decay heat. Ooi et al. [26] calculate the Natural convection Shutdown heat removal Test Facility (NSTF) for 8-channel open natural circulation loop using RELAP5-3D code. The oscillation length of mass flow rate and system pressure is well predicted compared with experimental data, but the void fraction and vapor generation rate show difference. They reported that the RELAP5-3D code demonstrated the capability to predict flow instability, however, discrepancies were observed. It is indicate that the further research is needed to predict oscillation accurately using system analysis code.

The summary of the investigated literatures is showed in Table I.

3. Conclusions

A literature review on prediction capabilities of system analysis code on DWO was performed. Based on survey results, the predictive capabilities of the current system analysis code are confirmed.

Most of the studies were conducted in conjunction with experiments to validate prediction capabilities of system analysis code. The system analysis code predicted well with oscillation period, mass flow rate, system pressure and so on, however, the calculations results are limited for straight tube or inclined tube, and shows the difference with amplitude, vapor generation etc. And also the studies indicated that the more investigations are needed to predict DWO accurately. This suggests that additional research is needed for the assessment of DWO with considering the prediction capabilities, such as vapor generation rate, oscillation amplitude etc., using system analysis codes

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