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Frequency-Domain Analysis of Density Wave Oscillations in SMART core

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1. Introduction

The onset of flow instability is an important design parameter particularly in an advanced pressurized water reactor (PWR) core which is designed to be operated at lower mass velocity conditions. When a constant pressure drop boundary condition is imposed on a boiling channel, an oscillatory channel flow readily occurs due to the resultant density wave oscillations. A fuel assembly channel with an oscillatory flow is highly susceptible to experience a critical heat flux (CHF), and the fuel integrity would be significantly deteriorated due to the mechanical vibration of the fuel channel. Many studies have been conducted to investigate the onset of a flow instability (OFI) specifically at BWR operating conditions. Although a substantial boiling may not occur at the core exit under PWR operating conditions, a reduced flow at abnormal or transient conditions could result in the OFI at the hot channels. Relatively sufficient margins at conventional PWR cores allow conservative analyses of OFI with a simple model. For advance PWRs which operated at lower mass velocities, the type-I and type-II instabilities have been studied in a boiling channel with unheated riser by employing the one-dimensional D-partition method[1].

A linear stability analysis model in a frequency domain is developed on the basis of the two-phase mixture equations and a neutron point kinetics model. Axial nodalization scheme was used for non-uniform axial power shapes and the marginal stability boundaries were evaluated in the SMART core.

2. Analysis

2.1 Establishment of a linear stability analysis model

A linear stability analysis model FAD(Frequency-domain Analysis of Density wave oscillations) was established in the frequency-domain in order to evaluate the stability margin in advanced PWR cores. The dynamics of a two-phase flow in a boiling channel was evaluated by employing one-dimensional drift-flux partially non-equilibrium model. The boiling channel consists of unheated inlet region, heated single-phase and two-phase regions, and unheated riser region. The continuity equations for the two-phase mixture and the gas phase can be expressed as the volumetric flux equation and the void propagation equation, respectively. They are,

$$\frac{\partial j}{\partial z} = \Omega \qquad (1)$$

$$\frac{\partial \alpha}{\partial t} + \left(C_0 j + V_{gj}^{g} \right) \frac{\partial \alpha}{\partial z} = \frac{\rho_m}{\Delta \rho} \Omega \qquad (2)$$

, where j, Ω, V_{gj}^{g}, C_0, α, ρ means volumetric flux, phase change frequency, drift velocity averaged at gas-phase, void distribution parameter, void fraction, and density, respectively. The mixture energy and momentum equations for the two-phase region are expressed as,

$$-\frac{\partial P}{\partial z} = \frac{\partial G}{\partial t} + \frac{\partial}{\partial z}\left(\frac{G^2}{\rho_m} \right) + \frac{G^2 f_{2\phi}}{2\rho_m d} + \rho_m g + \frac{\partial}{\partial z}\left(\frac{\rho_l \rho_g \alpha V_{gj}^{\,2}}{\rho_m (1-\alpha)} \right) \qquad (3)$$

$$\frac{\partial \left(\rho_m h_m \right)}{\partial t} + \frac{\partial \left(G h_m \right)}{\partial z} = \frac{q'' \xi}{A_f} - \frac{\partial}{\partial z}\left[\frac{\rho_l \rho_g \alpha V_{gj}}{\rho_m} \left(h_g - h_l \right) \right] \qquad (4)$$

, where V_{gj} means drift velocity averaged over the channel cross section. Thermal non-equilibrium effect was considered by employing Saha's subcooled boiling model[2].

The boiling channel was divided into several axial nodes. The integral balance equations for each axial node were linearized using the first-order perturbation technique. A perturbed inlet velocity propagates along the channel. It generates various perturbations as shown in Fig.1 which results in pressure drop perturbations in the single-phase and two-phase regions. The heat flux perturbation in the heated wall was calculated by employing a lumped parameter heat conduction equation for the fuel region. The reactivity feedback effects caused by the density and fuel temperature perturbations were reflected by a point kinetics model. The pressure drop perturbation generates a feedback perturbation of the inlet velocity due to the boundary condition which imposed a constant pressure drop on the boiling channel. That yields,

$$\delta \left(\Delta P_{1\phi} \right) + \delta \left(\Delta P_{2\phi} \right) = 0 \qquad (5)$$

The linearized time-domain differential equations for the perturbed variables were converted into an equivalent set of algebraic equations in the frequency-domain by the Laplace transformation method. The stability of the system was examined by applying the

Nyquist stability criterion[3] to the characteristic equation of the system that yields,

$$1+\Pi/\Gamma=0 \tag{6}$$

, where Γ and Π represent the transfer functions for the perturbation of single-phase and two-phase pressure drops, respectively.

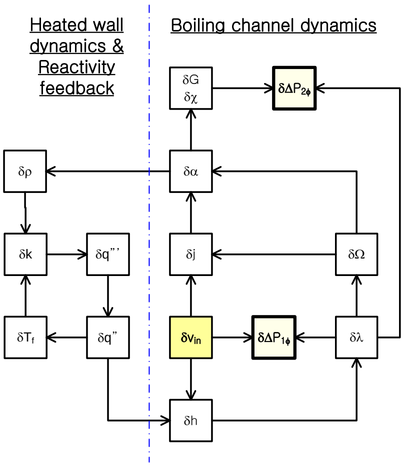

Figure 1. A diagram for the propagation of perturbations along a boiling channel.

2.2 Evaluation of stability margin in SMART core

The stability margin for SMART core operating conditions was evaluated for a hot subchannel as described in Table 1. The channel inlet and exit loss factors were calculated by considering the uncertainty of pressure loss coefficients and the effects of crud.

Table 1. Hot channel conditions

Parameters	Values
Channel hydraulic diameter, mm	11.8
Radial peaking factor	1.617
Pressure, MPa	14
Inlet temperature, ^{o}C	301
Channel inlet mass flux, kg/m^2s	1288
Channel inlet loss factor	3.8
Channel exit loss factor	7.1

The marginal stability boundary calculated by FAD code was compared with a simple model proposed by Ishii[4] which is given as,

$$N_{pch,eq}-N_{sub}=\frac{2\left[K_i+\dfrac{f_{2\phi}\cdot L}{2d}+K_e\right]}{1+\dfrac{1}{2}\left[\dfrac{f_{2\phi}\cdot L}{2d}+2K_e\right]} \tag{7}$$

As shown in Fig. 2, the stability boundary calculated by Ishii model was conservative in comparison with frequency-domain analysis by a linear model. Since a cosine axial power shape(APS) move the position of boiling boundary toward the center of the channel, it stabilized the system at low subcooling numbers due to the decrease of boiling length in comparison with a uniform APS. The reactivity feedback effect tends to stabilize the system.

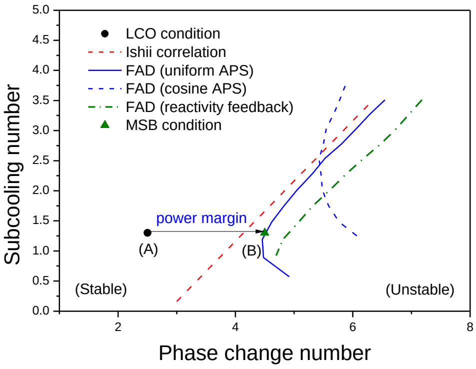

Figure 2. Comparison of marginal stability boundaries

The heat fluxes and oscillation periods at the OFI were calculated as Table 2 for the hot subchannel in SMART core. The power margin which is defined as $(Q_{OFI}-Q_{NOM})/Q_{NOM}$ was minimum for Ishii model.

Table 2. Hot channel conditions at OFI

Model	Heat flux(kW/m^2)	Period (sec)
Ishii model	1169	NA
FAD(uniform)	1492	1.05
FAD(cosine)	1991	0.69
FAD(feedback)	1624	0.84

Note: Nominal heat flux at hot channel in SMART≃600 kW/m^2

3. Conclusion

A linear stability analysis model was established in frequency-domain by employing drift-flux partially non-equilibrium equations and reactivity feedback from neutron point kinetics model. The power margin to the OFI was calculated as 95% and 149% by Ishii model and a linear model with uniform APS, respectively.

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