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The Generic Analysis Method for Core Flow Instability

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ABSTRACT

The generic analysis method for core flow instability is suggested to confirm that the core flow instability would not occur on PWR conditions. For the confirmation, the stability criteria of each fuel type are provided. Instability investigations in various accident conditions prove that the locked rotor accident is the most limiting case to instability. Parametric Effects are surveyed and in good agreement with available studies. The effects of heat flux distribution become negligible as the subcooling number is decreased. The power margin to instability is calculated quantitatively in various accident conditions.

1. Introduction

Boiling flows may be susceptible to thermodynamic instabilities. These flow instabilities are undesirable in boiling, condensing, and other two-phase flow devices for several reasons. Sustained flow oscillations can cause undesirable forced mechanical vibration of components, and can cause system control problems of particular importance in liquid-cooled nuclear reactor where the coolant acts as a moderator. And flow oscillation affect local heat transfer characteristics and boiling crisis. Therefore, the proper design criterion should be suggested and maintained to check the thermodynamic instabilities not occur.

There are various flow instabilities in two-phase flow instabilities[1,2]. Among these flow instabilities, two specific flow instability must be considered for PWR operation conditions: Ledinegg instability(flow excursion of static instability) and Density wave type of dynamic instability. The flow excursion or Ledinegg instability involves a sudden change in the flow rate to a low value. It occurs when the slope of the channel demand pressure drop-flow rate curve(internal characteristic of the channel) becomes algebraically smaller than the loop supply pressure drop-flow rate curve(external characteristic of the channel). The criterion for this instability is

$$\partial \triangle P / \partial \triangle G|_{int} \leq \partial \triangle P / \partial \triangle G|_{ext}. \quad (1)$$

Because the reactor coolant pump head has a negative slope $(\partial \triangle P / \partial \triangle G|_{ext})$ design, whereas the RCS pressure drop-flow rate curve $(\partial \triangle P / \partial \triangle G|_{int})$ has a positive slope, this instability would not occur (Figure 1).

The most common thermal-hydraulic instability, density wave oscillation in a heated channel has been described well by Lahey and Moody[3] and has been experimented in the closed channel systems[4,5]. Kao et al.[6] analyzed the parallel closed channel stability experiments simulating a reactor core flow and Ishii[7] developed the simplified stability criterion for parallel closed channel systems to evaluate whether a given condition is stable with respect to the density wave type of dynamic instability.

The purpose of this work is to confirm that the core flow instability will not occur in PWR reactor conditions with the generic analysis method. As a confirmation tool, the plot of instability map based on the each fuel type loss coefficients is suggested, and the limiting accident conditions from the instability standpoint is investigated. And also, the parametric effects are observed on core flow instability. Finally, the power margin to instability(density wave type of dynamic instability) through the evaluation of various accident conditions is calculated to see that the sufficient margin is available.

2. Ishii's Simple Method

2.1 Simplified Stability Criterion

Ishii's simple method consists of calculating the nondimensional parameters, namely the subcooling number(N_{sub}) and the equilibrium phase change number(N_{pch}) for the hot channel at the core operating conditions being analyzed. The following equations shows N_{sub} and $N_{pch,}$ respectively.

$$N_{sub} = \frac{\Delta\rho}{\rho_g}\frac{\Delta h_{sub}}{h_{fg}} \ . \tag{2}$$

$$N_{pch,eq} = \frac{\Omega_{eq}\,\ell}{v_{fi}} \ . \tag{3}$$

Based on these subcooling number(N_{sub}) and the equilibrium phase change number (N_{pch}), the point defined by (N_{sub},$N_{pch,eq}$) is plotted on the stability plane. The simplified stability criterion of Ishii which is a function of the channel geometry and a two-phase friction factor are as follows:

$$N_{pch,eq} - N_{sub} = X_{e,eq}\frac{\Delta\rho}{\rho_g} = \frac{2[k_i + \frac{f_m}{2D_e^*} + k_e]}{1+\frac{1}{2}[\frac{f_m}{2D_e^*} + 2k_e]} \ . \tag{4}$$

Using equation (2) and (3), we can simplified the left-hand side of stability line.

$$N_{pch,eq} - N_{sub} = \frac{\Delta\rho}{\rho_g h_{fg}}[\,(h_e - h_i)\frac{\rho_i}{\rho_f} - (h_f - h_i)] \ . \tag{5}$$

since $q_w\xi\,\ell = Q\ (heat\ input),\ \ \rho_i A v_{fi} = \dot{m}\ (mass\ flow\ rate),$

$Q/\dot{m} = h_e - h_i,\ \ \Delta h_{sub} = h_f - h_i,$ and $\Delta\rho = \rho_f - \rho_g$.

The validity of the stability criterion of the equation (4) was shown in the reference[1] and holds only if $N_{sub} > (N_{sub})_{cr}$.

where $$(N_{sub})_{cr} = \frac{154A}{\xi\,\ell}(N_{pch})_0 \ . \tag{6}$$

2.2 Power Margin Calculation

Equalizing the equation (4) and (5), we can calculate the power margin to instability and determine the h_e ($=h_{e,max}$) which causes the condition being analyzed to fall on the stability line. Therefore, $q_{max} = \frac{\dot{m}_{hc}}{F^N_{\wedge H}} (h_{e,max} - h_i)$. (7)

where $\dot{m}_{hc} = hot\ channel\ mass\ flow\ rate = \dot{m}(1 - Bypass)$.

Then, the power margin to instability = $\frac{q_{max}}{q_w}$. (8)

3. Application to PWR Conditions

3.1 Stability Plane for Each Fuel Type

To achieve the relationship between the stability line and each fuel type, generic values of inlet and outlet loss coefficients are used for various fuel assembly type[8]. Table 1 shows that the inlet and outlet loss coefficient of each fuel assembly at the Reynolds No = 500,000 and calculated value of equation (4). For two-phase mixture friction factor, we used the Thom's multiplier for pressure drop correlation[9] and the single-phase friction factor(bare rod+grid loss) at saturation condition.

As a result of plotting the stability plane, each fuel type provides the similar stability criterion as shown in Figure 2.

3.2 The Instability of Limiting Accidents

To investigate the instability of limiting accident conditions, ULCHIN Unit 1 and 2 are selected as a reference plants. For each accident condition, the most limiting channel which gives the minimum DNBR is obtained using by THINC-IV subchannel code[10]. Based on obtained core conditions and flow property, N_{sub} and N_{pch} can be determined for the hot channel. Figure 3 shows that the locked rotor is the most limiting accident condition to instability, and, even for locked rotor accident, there is still plenty of available margin against instability criterion.

3.3 Parametric Effect on instability

The parametric effects(Figure 4) are observed to confirm this generic analysis method to available reference. Table 2 lists the surveyed parameters and the tendency of instability. Increase of power, bypass flow and heated length gives less stability. This result is in good agreement with the available studies[2]. The decrease of system pressure destabilize the system. The effect of heat flux distribution is investigated considering the uniform heat flux and 1.55 chopped cosine heat flux. 1.55 chopped cosine heat flux distribution makes the system more unstable than uniform distribution. However, the difference become negligible at the certain subcooling number.

3.4 Quantifying the Power Margin to Instability

Based on the equations (7) and (8), the power margin to instability is calculated through the evaluation of various accident conditions. The power margins(Figure 5) are expressed as a percent of rated reactor power. For ULCHIN unit 1 and 2, the locked rotor accident is the most limiting case and the power margin is calculated as 151.3%.

4. Conclusions

The generic analysis method for core flow instability is suggested to confirm that the core flow instability would not occur on PWR conditions. The stability criteria are not dependent critically on each fuel type, and instability investigations in various accident conditions prove that the locked rotor accident is the most limiting case to instability. However, even for locked rotor accident, there is still plenty of available margin against instability criterion. The survey of parametric effects resulted in good agreement with available studies. The effect of heat flux distribution becomes negligible as the subcooling number is decreased. Further studies are necessary to ascertain the observed effect. The power margin to instability is calculated quantitatively in various accident conditions. The power margin for locked rotor accident is 151.3%. Consequently, PWR plants, for example, ULCHIN unit 1 and 2, have an enough margin to instability.

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NOMENCLATURE

A	*flow area of channel* (ft^2)	ξ	*heated perimeter* (ft)

cm two−phase friction factor coefficient

D_e^* nondimensional hydraulic diameter $= D_e / \ell$

f_m two−phase mixture friction factor $= cm * fs$

h_i inlet enthalpy (Btu/lb)

ℓ length of heated channel (ft)

v_{fi} velocity at inlet of channel (ft/sec)

$\Delta\rho$ $\rho_f - \rho_g$

Δh_{sub} inlet subcooling $= h_f - h_i$ (Btu/lb)

h_{fg} latent heat of vaporization (Btu/lb)

k_i, k_e inlet and exit loss coefficient

q_w wall heat flux $(Btu/hr\,ft^2)$

fs single−phase friction factor at saturation conditions

$(N_{pch})_0$ value corresponding to zero subcooling at the inlet $= X_e \dfrac{\rho_f - \rho_g}{\rho_g}$

Ω_{eq} equilibrium frequency of phase change $= \dfrac{\Gamma_{g,eq}\,\Delta\rho}{\rho_g\,\rho_f}$

$\Gamma_{g,eq}$ mass rate of vapor generation per unit volume $= \dfrac{q_w \xi}{A h_{fg}}$

Table 1. Inlet and outlet loss coefficients for Fuel Assembly and the value of Equation (4)

Fuel Type	Inlet loss coefficient(k_i)	Outlet loss coefficient(k_e)	$N_{pch,eq}$ - N_{sub}
14x14 OFA	4.56	3.61	3.772
16x16 STD	3.11	2.80	3.575
17x17 V5H	2.90	2.80	3.550
17x17 KOFA	2.38	1.82	3.566

Table 2. Parametric Effect on Instability

parameters	Reference Value	Variation	Change Value	Probability of Instability
Power	0.9668	1.05	8.61% increase	Increase
Bypass Flow(%)	5.6	11.2	5.6% increase	Increase
Heated Length(in)	143.7	147.1214	3.4214 in increase	Increase
		133.4358	10.2642 in decrease	Decrease
Pressure(psia)	2250.0	2200.0	50 psia decrease	Increase
Heat Flux Dist.	Uniform	1.55 chopped cosine	-	Increase first and negligible as N_{sub} ↓

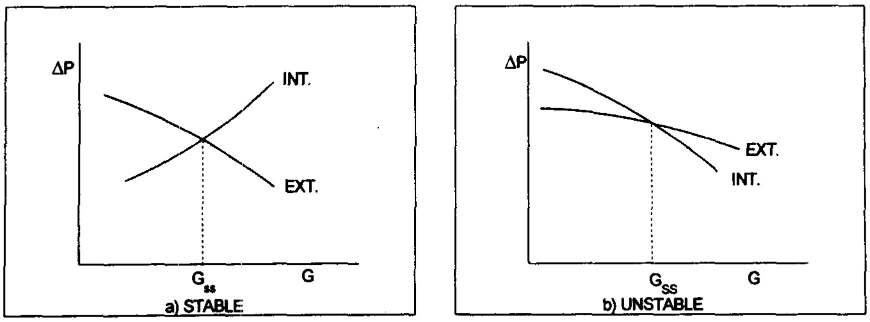


Figure 1. Pressure Drop Characteristics

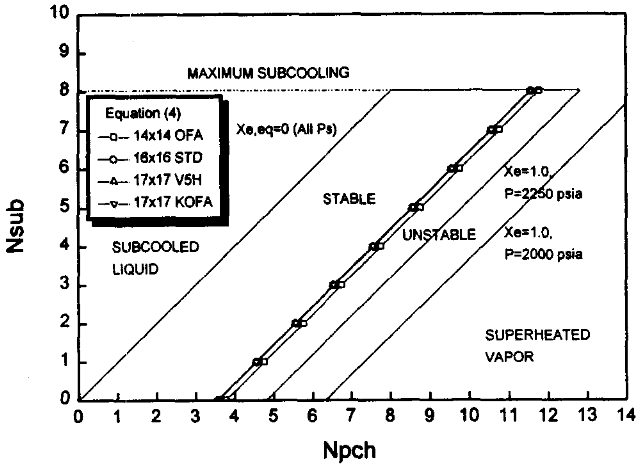


Figure 2. Stability Plane for Each Fuel Type

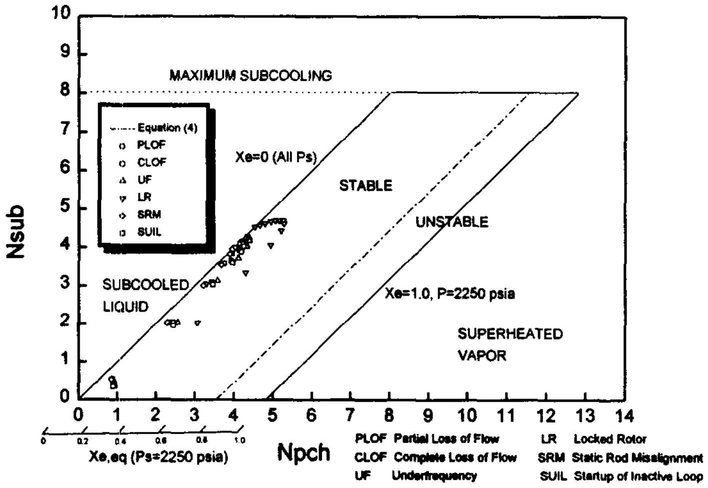
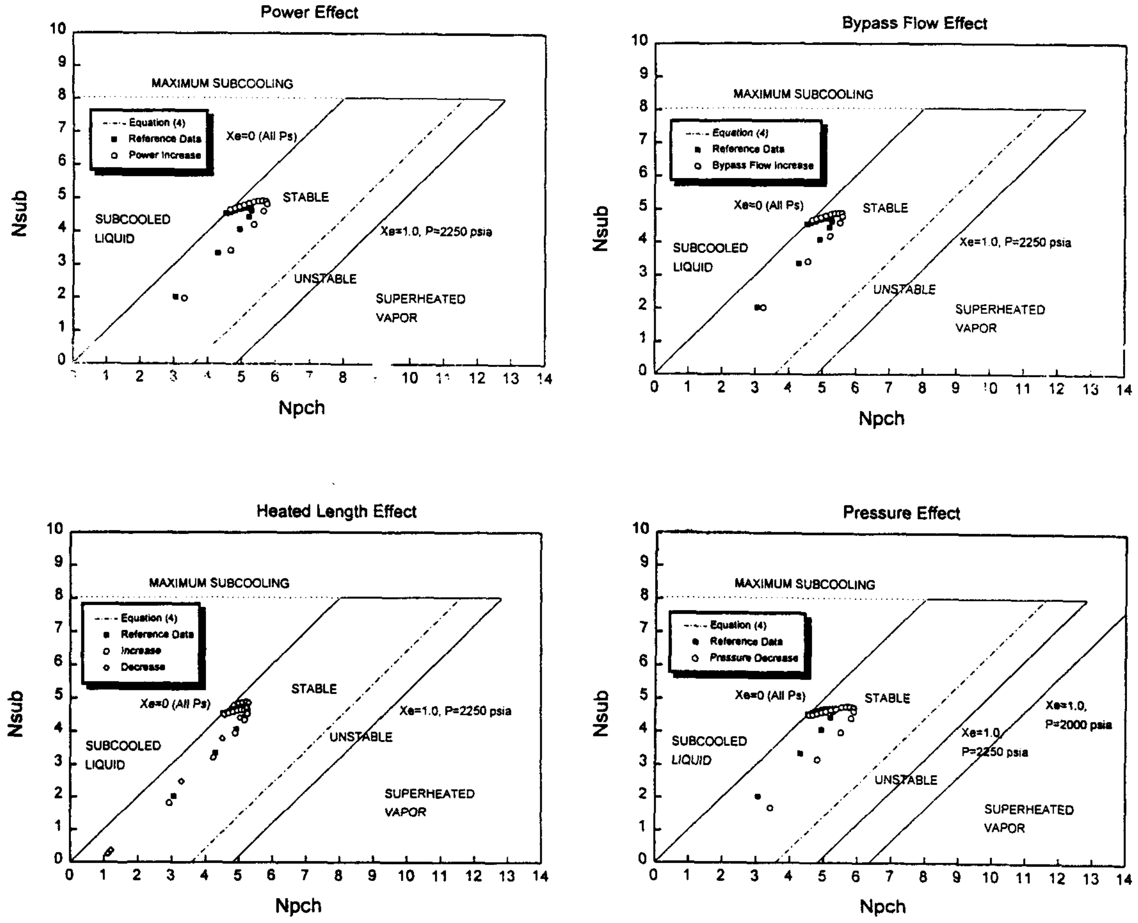


Figure 3. Limiting Accident Condition to Instability



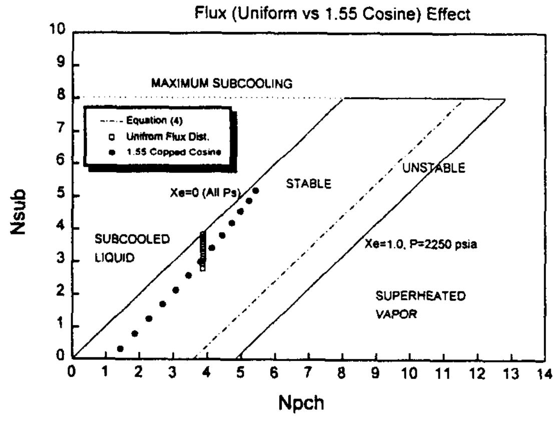


Figure 4. Parametric Effect on Instability

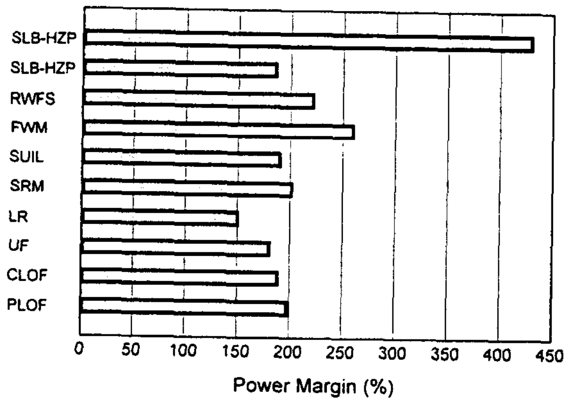


Figure 5. Power Margin for ULCHIN Unit 1&2