THE IMPACT OF VERTICAL ACCELERATION ON THE NONLINEAR BEHAVIORS OF MULTIPLE PARALLEL BOILING CHANNELS

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ABSTRACT

This study adopts the multiple boiling channel model developed previously by the authors and the external force method regarding the seismic induced vertical acceleration to investigate the effects of seismic vibration on the system's nonlinear behaviors. With the normal operating state of an ABWR as a reference case, the influences of seismic parameters, i.e. peak acceleration and vibration frequency, and system parameters, such as inlet subcooling, axial power distribution, channel length, inlet and outlet loss coefficients, on the system behaviors are carried out in this study. The impact of external vertical acceleration on the system transients may depend on their imposed amplitudes and frequencies. For this multi-channel boiling system, the dominating effect of vertical accelerations may interact with channel-to-channel interactions to present more complex nonlinear oscillations. The strengths of resonance oscillations are consistent with the stability degree of the initial state when the seismic vibration frequency is equal to the system's natural frequency. The preliminary analysis indicates that the natural circulation system is more susceptive to the impact of seismic acceleration with respect to the forced circulation system.

KEYWORDS
Two phase flow, multiple boiling channels, nonlinear analysis, vertical acceleration

1. INTRODUCTION

Density wave oscillations (DWOs) are a typical type of dynamic instability occurring in the boiling system [1]. The self-sustained DWOs are well-known to be triggered by the multiple thermal-hydraulic feedbacks among flow rate, pressure drop, flow enthalpy and density or void fraction. Most two-phase flow systems, i.e. boiling water reactors (BWRs) and advanced boiling water reactors (ABWRs), consist of multiple parallel boiling channels, which channel-to-channel interactions can distribute over the channels. The studies concerning DWOs combined with parallel channel instability are of significant interest for the design, operation and safety of such systems. The seismic vibrations may result in the perturbations of the

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flow properties, i.e. void fraction distribution, which may further cause the power oscillations due to the void-reactivity feedback. The effect of the seismic vibration together with multiple channel interactions should be an interesting topic on the reactor thermal hydraulics.

Earthquake wave forms can be divided into four major kinds: S-waves, P-waves, LR-waves and LQ-waves, where S-waves and P-waves are body waves and LR-waves and LQ-waves are surface waves [2]. The vibration frequency of earthquake is usually less than 20Hz, ranged from 0.1Hz to couple tens of Hz and inaudible due to the low frequency. The vibration amplitude may not be large and is usually in the order of millimeters. However, it can result in much larger displacement for a tall building. For the case of fuel rods in a nuclear power plant, the maximum displacement of the rod top can be about the order of 2cm. In order to simulate the seismic vibration conditions, the study should involve the vibration characteristics, including frequency and amplitude of seismic acceleration.

The limited studies [3-5] were performed to investigate the effect of seismic vibration on the two-phase flow behavior and the system stability. Hirano and Tamakoshi [3] employed TRAC-BF1 to simulate the impact of vertical seismic acceleration on the thermal-hydraulic stability of a BWR. They found the seismic induced influence might depend on the strength of the seismic wave and the stability degree of the initial states. When the frequency of seismic wave was the same as the natural frequency of the system flow, they would lead to a resonance oscillation. Satou et al. [4] took TRAC-BF1/SKETCH-INS to study the neutron-coupled thermal hydraulic behaviors of a BWR under seismic acceleration. They revealed the external acceleration had the capability to cause the resonance with both core-wide and regional instabilities. Especially the vertical acceleration rather than the horizontal one would induce strongly influence on the core power oscillations.

With the above brief review, this paper employs the multiple boiling channel model [6] and the external force method [5] to investigate the effects of vertical acceleration as well as parametric effects on the system dynamics.

2. THE MODEL

Hirano and Tamakoshi [3] and Satou et al. [4] reported that the vertical seismic motion rather than those in the other directions could induce more significant impact on the system and fluid oscillations. Therefore, to simplify the analysis, this study only considers the seismic effect in the vertical direction. The nature of vertical vibration imposed by the earthquake, mostly from surface waves, can be regarded as a composite of coupling sinusoidal waves with different amplitudes and frequencies. The fundamental form can be expressed as:

$$H(t) = \sum_k A_k \sin(2\pi f_k t) \tag{1}$$

Where $H(t)$ is the position of the flow channel under vertical vibration, A_k is the amplitude and f_k is the frequency of the k-th sinusoidal wave, respectively.

Taking the first and second time derivatives of Eq. (1) can lead to the expressions of velocity and acceleration caused by the vertical seismic motion. Thus,

$$u(t) = \sum_k 2\pi f_k A_k \cos(2\pi f_k t) = \sum_k u_{peak,k} \cos(2\pi f_k t) \tag{2}$$

$$a(t) = \sum_k -4\pi^2 f_k^2 A_k \sin(2\pi f_k t) = \sum_k a_{peak,k} \sin(2\pi f_k t) \tag{3}$$

Where $u_{peak,k} = 2\pi f_k A_k$ is the peak velocity, and $a_{peak,k} = -4\pi^2 f_k^2 A_k = -a_{\max,k} g$ is the peak acceleration, of the k-th sinusoidal wave.

The present study adopts the nonlinear dynamic model for the multiple boiling channels developed previously by the authors [6]. To facilitate the explanation and discussion of the results, the assumptions and dynamic equations are briefly presented. By adopting the homogeneous two-phase flow model and considering the j-th channel in the system of M parallel channels subject to vertical seismic vibration shown in Fig.1, the following assumptions are made to simplify the problem:

- Each flow channel and the whole system are rigid.
- Constant properties at the system pressure are used under both steady and dynamic conditions,
- The heat flux is assumed to be uniform in the axial direction for each channel,
- All channels have the same inlet subcooling,
- Subcooled boiling is not considered, and
- Constant system flow rate is supposed during seismic motions.

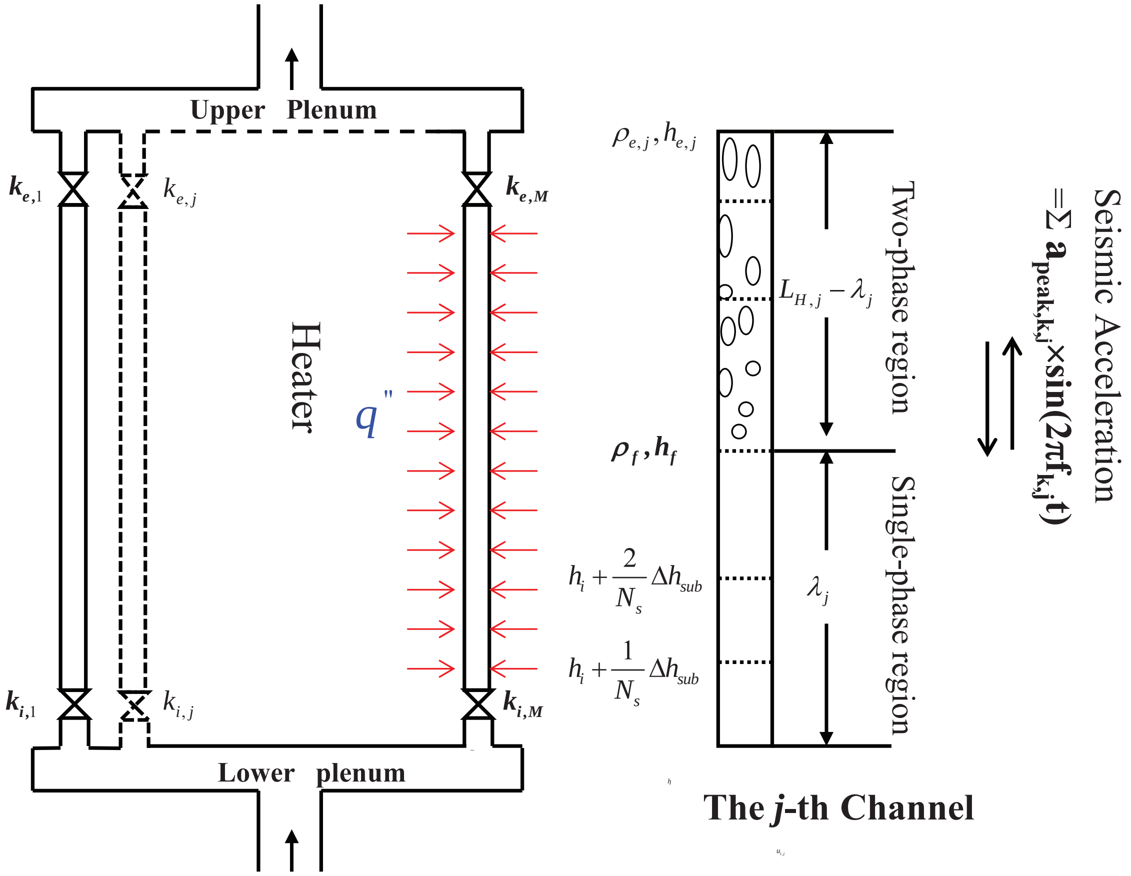

Figure 1. Schematic of a Multiple Boiling Channel System under Vertical Seismic Acceleration.

Based on the assumptions and adopting the external force method [5] that only considers the external acceleration induced by the seismic vibration, the non-dimensional conservation equations for the j-th channel under external vertical acceleration can be got as:

$$\frac{\partial}{\partial t^+}\rho_j^+ + \frac{\partial}{\partial z^+}\left(\rho_j^+ u_j^+\right) = 0 \tag{4}$$

$$\frac{\partial}{\partial t^+}\left(\rho^+_j h^+_j\right)+\frac{\partial}{\partial z^+}\left(\rho^+_j h^+_j u^+_j\right)=q^{''+}_j \tag{5}$$

$$\frac{\partial}{\partial t^+}\left(\rho^+_j u^+_j\right)+\frac{\partial}{\partial z^+}\left[\rho^+\left(u^+_j\right)^2\right]=-\frac{\partial P^+_j}{\partial z^+}-\frac{fL_H}{2D}\rho^+_j\left(u^+_j\right)^2-\sum_{m=1}^{N}k_m\delta\left(z^+_j-z^+_m\right)\frac{\rho^+_j\left(u^+_j\right)^2}{2}-\frac{1}{Fr}\rho^+_j g^*_j \tag{6}$$

Where g^*_j represents the vertical acceleration term for the j-th channel contributed by both the gravity and seismic accelerations, which is expressed as:

$$g^*_j=\begin{cases}1+\sum_k a_{\max,k,j}\sin(2\pi f^+_{k,j}t^+), & under\ seismic\ motion\\ 1, & in\ normal\ condition\end{cases} \tag{7}$$

The integration of the momentum equation, Eq. (6), from the inlet to the outlet of the j-th channel, originally from Clausse and Lahey [7], leads to an expression for the pressure drop through the channel [6].

$$\Delta P^+_j=M^+_{ch,j}\frac{du^+_{i,j}}{dt^+}+\Delta P^+_{H,j}\qquad , j=1,2,\ldots,M \tag{8}$$

Where

$$\begin{aligned}\Delta P^+_{H,j}=&\frac{\left(1-M^+_{ch,j}\right)}{\left(1/\rho^+_{e,j}\right)-1}\left[\left(1-\lambda^+_j\right)\frac{dN_{Zu,j}}{dt^+}-N_{Zu,j}\frac{d\lambda^+_j}{dt^+}\right]+\frac{dM^+_{ch,j}}{dt^+}\left[u^+_{i,j}-\frac{N_{Zu,j}\left(1-\lambda^+_j\right)}{\left(1/\rho^+_{e,j}\right)-1}\right]\\&+\frac{d\rho^+_{e,j}}{dt^+}\left[\frac{N_{Zu,j}\left(1-\lambda^+_j\right)}{\left(1-\rho^+_{e,j}\right)^2}\left(1-M^+_{ch,j}\right)\right]+\left\{\frac{M^+_{ch,j}}{Fr}+\frac{N_{exp}N_{sub}}{Fr}\left[\lambda^+_j-\frac{1}{2N_s}\sum_{n=1}^{Ns}(2n-1)\left(L^+_{n,j}-L^+_{n-1,j}\right)\right]\right\}\times g^*_j\\&+\left(1+\frac{k_{e,j}}{2}\right)\rho^+_{e,j}u^{+^2}_{e,j}+\left(\frac{k_{i,j}}{2}-1\right)u^{+^2}_{i,j}+\Lambda_{1\phi,j}\lambda^+_j u^{+^2}_{i,j}+\Lambda_{2\phi,j}\left\{\frac{1-\lambda^+_j}{\frac{1}{\rho^+_{e,j}}-1}u^{+^2}_{i,j}\,ln\left(\frac{1}{\rho^+_{e,j}}\right)+\frac{2u^+_{i,j}N_{Zu,j}\left(1-\lambda^+_j\right)\left(1-M^+_{ch,j}\right)}{\frac{1}{\rho^+_{e,j}}-1}\right.\\&\left.+\left(\frac{N_{Zu,j}\left(1-\lambda^+_j\right)}{\frac{1}{\rho^+_{e,j}}-1}\right)^2\left[\left(\frac{1}{\rho^+_{e,j}}-3\right)\frac{1-\lambda^+_j}{2}+M^+_{ch,j}-\lambda^+_j\right]\right\}\end{aligned} \tag{9}$$

On the basis of continuity equation, Eq. (4), and energy equation, Eq. (5), the following set of equations for the dynamics of multiple boiling channels can be derived [6]:

$$\frac{dL^+_{n,j}}{dt^+}=2u^+_{i,j}-2N_s\frac{N_{Zu,j}}{N_{sub}}(L^+_{n,j}-L^+_{n-1,j})-\frac{dL^+_{n-1,j}}{dt^+}\qquad , n=1,2,\ldots.,N_s\ ;\ j=1,2,\ldots.,M \tag{10}$$

$$\frac{dM^+_{ch,j}}{dt^+}=u^+_{i,j}-\rho^+_{e,j}u^+_{e,j}\ ,\quad j=1,2,\ldots.,M \tag{11}$$

$$M_{ch,j}^{+} = \lambda_j^{+} + (1-\lambda_j^{+})\frac{\rho_{e,j}^{+}\ln(\rho_{e,j}^{+})}{\rho_{e,j}^{+}-1} \tag{12}$$

$$\frac{d\rho_{e,j}^{+}}{dt^{+}} = \left\{\left[1+\frac{\rho_{e,j}^{+}\ln\left(\rho_{e,j}^{+}\right)}{1-\rho_{e}^{+}}\right]\frac{d\lambda_j^{+}}{dt^{+}} + \rho_{e,j}^{+}u_{e,j}^{+} - u_{i,j}^{+}\right\} \times \frac{\left(1-\rho_{e,j}^{+}\right)^2}{\left(1-\lambda_j^{+}\right)\left[1-\rho_{e,j}^{+}+\ln\left(\rho_{e,j}^{+}\right)\right]} \tag{13}$$

$$u_{e,j}^{+} = u_{i,j}^{+} + N_{Zu,j}(1-\lambda_j^{+}) \tag{14}$$

The multiple parallel channels shown in Fig. 1 must meet the following two boundary conditions. Since all the channels share common lower and upper plenums, they have the same pressure drop. Thus,

$$\Delta P_1^{+} - \Delta P_j^{+} = 0, \quad j = 2,3,....,M \tag{15}$$

And, the summation of the mass flow rate through each channel must be equal to the total mass flow rate. In this study the system is assumed to have a constant total mass flow rate during transients and is kept at the steady-state value. Thus,

$$\sum_{j=1}^{M} A_{x-s,j}^{+}\frac{du_{i,j}^{+}}{dt^{+}} = 0 \tag{16}$$

On the basis of Eq. (15) and Eq. (16), the inlet flow dynamics of multiple boiling channels with constant total mass flow rate, with or without vertical seismic accelerations, can be expressed as [6]:

$$\frac{du_{i,j}^{+}}{dt^{+}} = A_j\frac{du_{i,1}^{+}}{dt^{+}} + B_j \ , \quad j = 2,3,....,M \tag{17}$$

$$\frac{du_{i,1}^{+}}{dt^{+}} = \frac{-\sum_{j=2}^{M} A_{x-s,j}^{+}B_j}{1+\sum_{j=2}^{M} A_{x-s,j}^{+}A_j} \tag{18}$$

$$A_j = M_{ch,1}^{+} / M_{ch,j}^{+} \tag{19}$$

$$B_j = (\Delta P_{H,1}^{+} - \Delta P_{H,j}^{+}) / M_{ch,j}^{+} \tag{20}$$

3. SOLUTION METHOD

Before the seismic motions are imposed, the system is in its original steady state. The steady-state inlet velocity of each channel and the other variables are determined by solving the set of equations with time derivative terms set to zero, thereby resulting in a set of nonlinear algebraic equations. This set of equations is solved numerically using the subroutine SNSQE of Kahaner et al. [8], employing the Powell Hybrid Scheme. By assuming the hypothetical vertical accelerations during seismic motions, the nonlinear dynamics of the system at a given initial steady state are obtained by solving the set of nonlinear, ordinary differential equations using the subroutine SDRIV2 of Kahaner et al. [8]. The SDRIV2 employs the Gear multi-value method.

4. RESULTS AND DISCUSSION

4.1 Model Validation

The multiple boiling channel model employed in the present study are validated against the experimental data of Guo et al. [9]. The part of multiple boiling channel model involving single-phase inlet section, heated section and riser is adjusted to meet the structure of twin-channel experimental loop in Guo et al. [9]. The results in Fig. 2 indicate that the present multiple boiling channel model can reasonably predict the stability boundary of two equal-heating channels with symmetric inlet throttling for given mass flow rates. Although the present model underestimates the threshold powers compared with experimental data in the medium and high subcooling number regions, the predicted results can address the major trend of stability boundary as shown in Fig. 2. The discrepancy may be resulted from the model simplicities, i.e. the use of homogeneous two-phase flow model, and the experimental uncertainties. In addition, this study also predicts the stability boundary in the low inlet subcooling number region, for which the experimental data is lacking, and reveals the whole stability boundary of two equal-heating channels with an "*L*" shape.

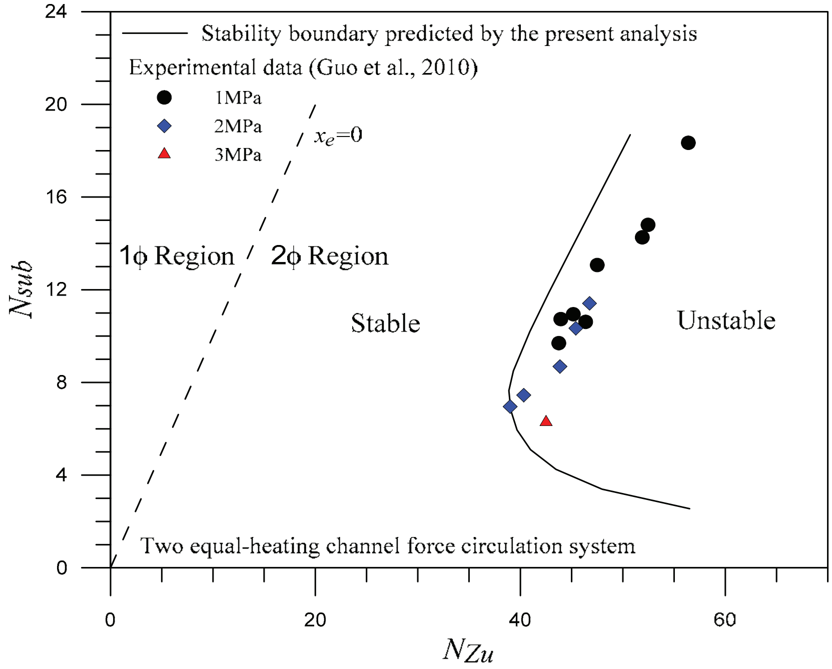

Figure 2. The Comparisons between the Model Predictions against the Experimental Data [9].

Table I. The geometries and normal operating properties used in the present study (mainly based on the PSAR data of ABWR [10]).

Parameter	Value	Parameter	Value	Channel Number	Heat Flux Ratio (Ch.1:Ch.2)	Inlet loss coefficient (k_i)
P	72.7 bar	u_{i0}	1.96 m/s	Two	1.1:0.9	23.27, 68.25
Q	3926 MWt	h_i	1227 kJ/kg			
L_H	3.81 m	$f_{1\phi}$	$0.14Re^{-0.1656}$			
A_H	8.169 m^2	k_e	0.68			
D_H	0.01 m					

4.2 The Stability Map and Hypothetical Seismic Acceleration

Table I lists the geometries and normal operating properties used in the present study. This set of data is mainly extracted from the Preliminary Safety Analysis Report of an ABWR [10]. The set of inlet loss coefficient corresponding to the two boiling channels with a heat flux ratio of 1.1:0.9 is selected such that these two channels have approximately the same exit quality.

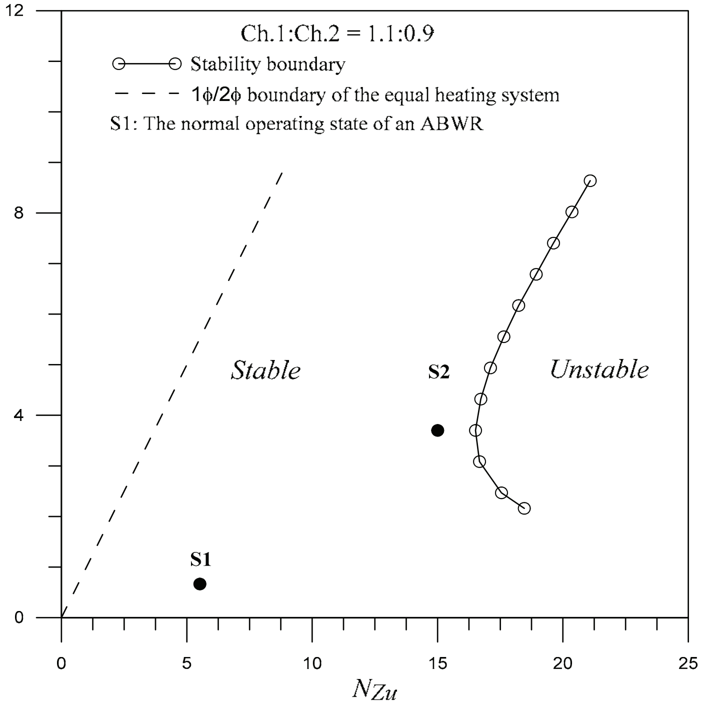

Figure 3. The Thermal-Hydraulic Stability Boundary of a Two Boiling Channel System with a Heat Flux Ratio of 1.1:0.9.

Figure 3 illustrates the thermal-hydraulic stability boundary of a two boiling channel system with a heat flux ratio of 1.1:0.9 and a constant total flow rate under the parameters given in Table I on the plane of the subcooling number (N_{sub}) and the average Zuber (phase change) number (N_{Zu}). The results indicate that the ABWR normal operating state of N_{sub}=0.665 and N_{Zu}=5.518, denoted as S1 point shown in Fig. 3, is away from the stability boundary got by the present analysis. This means it is a very stable state.

The effect of external vertical acceleration on the system transient is firstly evaluated in the S1 stable state as marked in Fig. 3. The natural frequency of S1 state is about f^{+}=0.378. The seismic induced oscillation can be considered as the combined result of the system natural oscillation interacting with the influence of vertical seismic acceleration. Figure 4(a) represents the hypothetical seismic acceleration with (a_{peak}, f^{+}), in which the first two vertical acceleration waves of (0.1g, 0.378) designated appear alone with a non-seismic time interval and finally the coupling wave of these two accelerations follows. Figure 4(b) displays the transient responses of the S1 state subject to these vertical accelerations. The results reveal that the impact of vertical seismic acceleration would dominate the system behaviors. The oscillation frequency in each channel is the same as the seismic frequency and the system quickly return to its original steady state if external seismic vibration is dismissed. The superposition of two identical vertical acceleration waves can result in a larger oscillation with about two times of amplitude induced by a single wave alone, as eventually shown in Fig. 4(b). Although the seismic frequency in this case is set to the system's natural frequency, the seismic induced oscillation remains bound, implying that may not result in an uncontrollable resonance oscillation of S1 state under such vertical accelerations imposed, as revealed in Fig. 4(b). Moreover, the two asymmetric heating channels oscillate with the same amplitude but out-of-phase to keep the system flow rate constant.

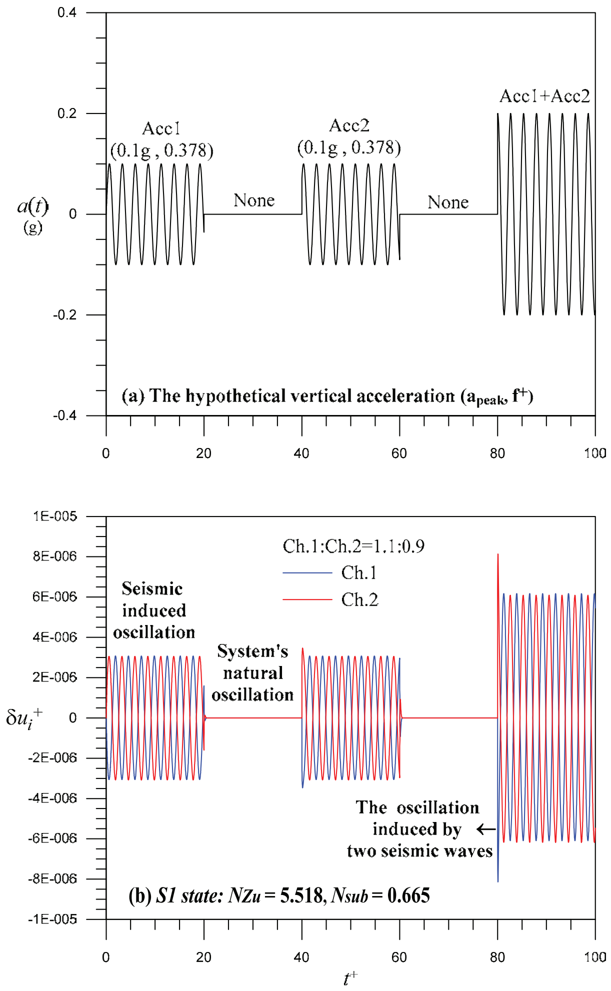

Figure 4. The Effect of Vertical Acceleration on the Transient Response of the S1 State, (a) Hypothetical Seismic Acceleration; (b) Seismic Induced Oscillation.

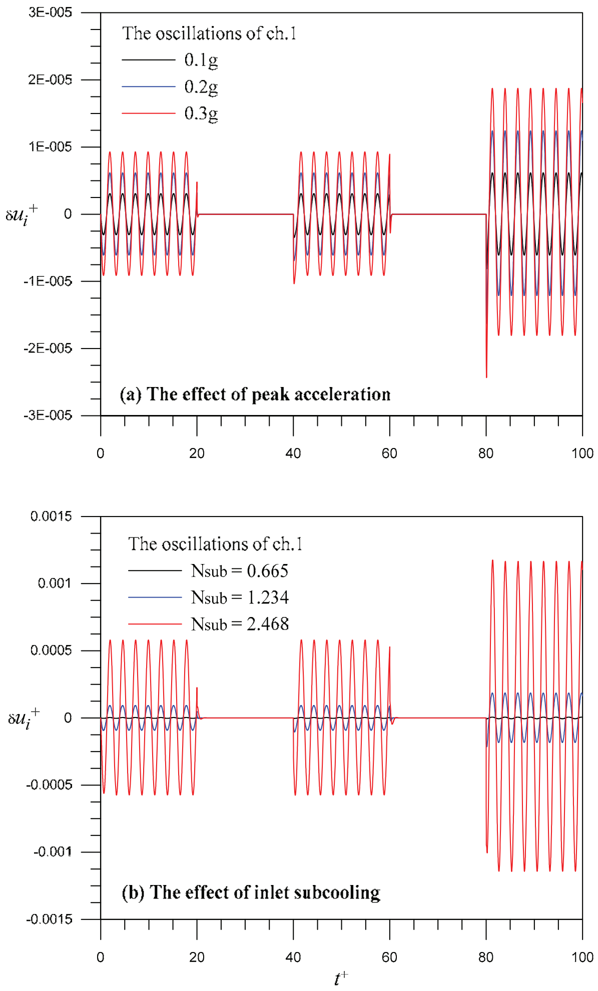

Figure 5. The Parametric Effects on the Transient Response of the S1 State, (a) Peak Acceleration; (b) Inlet Subcooling.

4.3 The Parametric Effects on the Seismic Induced Oscillations

The parametric effects, including seismic and system parameters, on the seismic induced oscillations are evaluated by comparing with the reference case of Fig. 4. The influence of the vertical peak acceleration induced by external vibration on the system transients is revealed qualitatively in Fig. 5(a) by changing the magnitude of peak acceleration from 0.1g, 0.2g to 0.3g. The results in channel 1 show that a larger acceleration imposed on the system will lead to a higher oscillation. If further enlarge the vertical acceleration, the system oscillation will be getting larger and larger and eventually cause the occurrence of reverse flow. On the other hand, the effect of inlet subcooling on the system dynamics is evaluated by step increase from N_{sub} = 0.665, 1.234 to 2.468, as indicated in Fig. 5(b). The figures illustrate that the seismic induced oscillation in channel 1 of higher inlet subcooling would persist a larger oscillation with respect to that of lower inlet subcooling. This may be explained by the system nature and the seismic impact. Increasing the inlet subcooling over this range considered would move the system more close to the stability boundary as revealed in Fig. 3. In addition, the effect of seismic vibration on the system in the present analysis is consistent with the vertical acceleration term, g_j*, through the gravitational pressure drop in Eq. (9). Increasing the inlet subcooling would result in a larger pressure drop additionally contributed by the external vertical acceleration, and thus enlarge the seismic effect to destabilize the system.

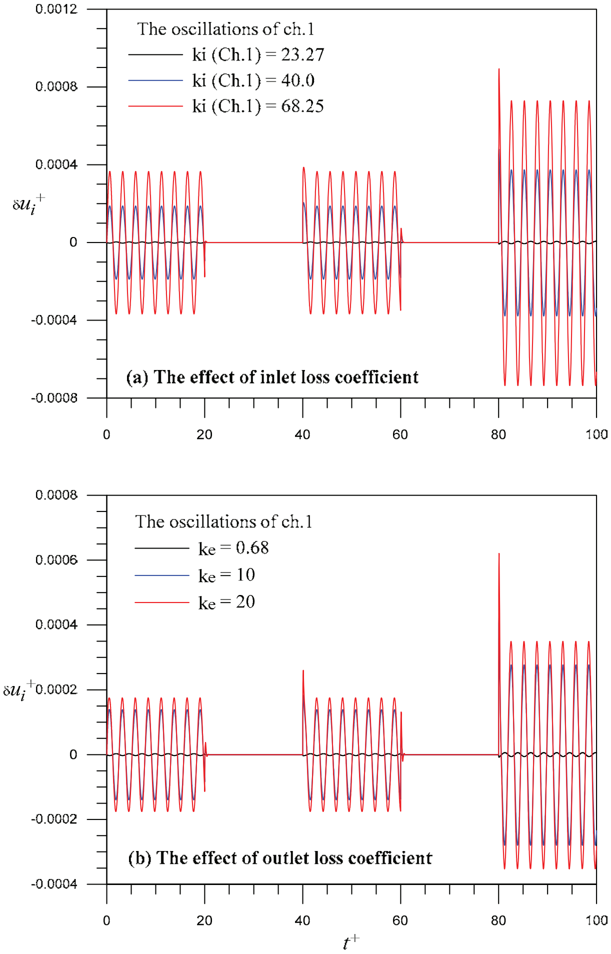

Figure 6. The Parametric Effects on the Transient Response of the S1 State, (a) Inlet Loss Coefficient; (b) Outlet Loss Coefficient.

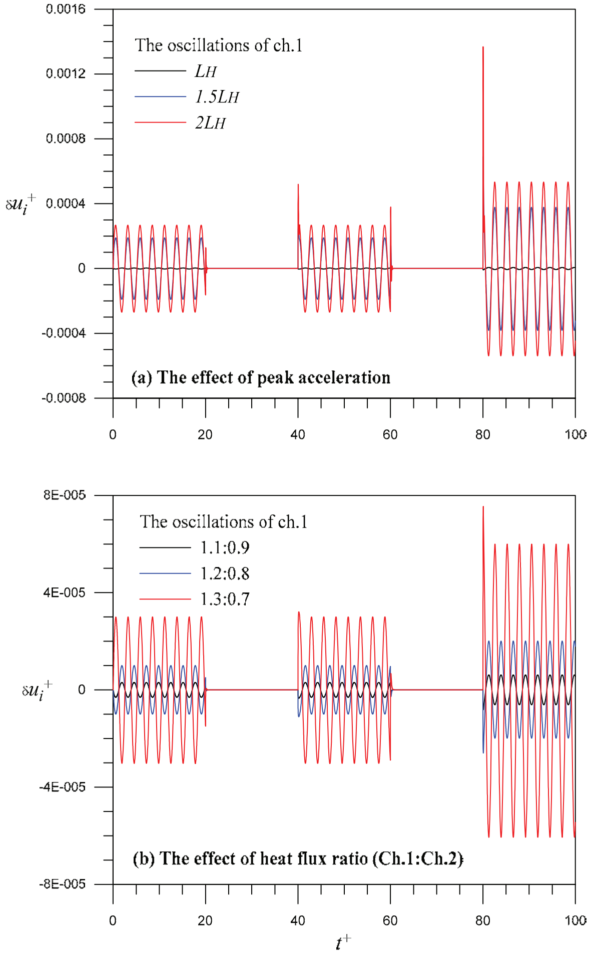

Figure 7. The Parametric Effects on the Transient Response of the S1 State, (a) Channel Length; (b) Heat Flux Distribution.

Figure 6 illustrates the effects of inlet loss coefficient (k_i) in channel 1 and outlet loss coefficient (k_e) on the seismic induced oscillations. The results indicate that the system with a larger inlet loss coefficient in channel 1 or outlet loss coefficient would destabilize the seismic induced oscillations. As mentioned earlier, the set of inlet loss coefficient in Table I is selected to meet the requirement of the asymmetric heating channels with nearly the same exit quality, i.e. a similar power-to-flow ratio between channels, in normal operation. Increasing the inlet loss coefficient in the more heated channel, i.e. channel 1, will lead to a less channel flow rate distributing in this channel. This tends to cause an unexpectedly higher power/flow ratio in such channel than in the others and a more unstable channel-to-channel interaction, as a result of the more difference between channels, to destabilize the system as illustrated in Fig. 6(a). On the other hand, the increase in the outlet loss coefficient of these two asymmetric heating channels would contribute to a larger two-phase pressure drop and thus a more unstable channel-to-channel interaction to destabilize the seismic induced oscillations as revealed in Fig. 6(b).

This study further evaluates the parametric effects of channel length and heat flux distribution on the seismic induced oscillations as shown in Fig. 7. The results in Fig. 7(a) indicate that increasing the channel length would lead to a longer two-phase section and a larger pressure drop additionally contributed by external vertical acceleration. These will both enhance the seismic induced effect to destabilize the system. Moreover, the results in Fig. 7(b) reveal that the influence of heat flux distribution on the seismic induced oscillations. A more asymmetric heating power distribution implies enlarging the power difference between channels. This may result in a more unstable channel-to-channel interaction to destabilize the seismic induced oscillations.

4.4 The Effects of Coupling Seismic Waves and Resonance Oscillations

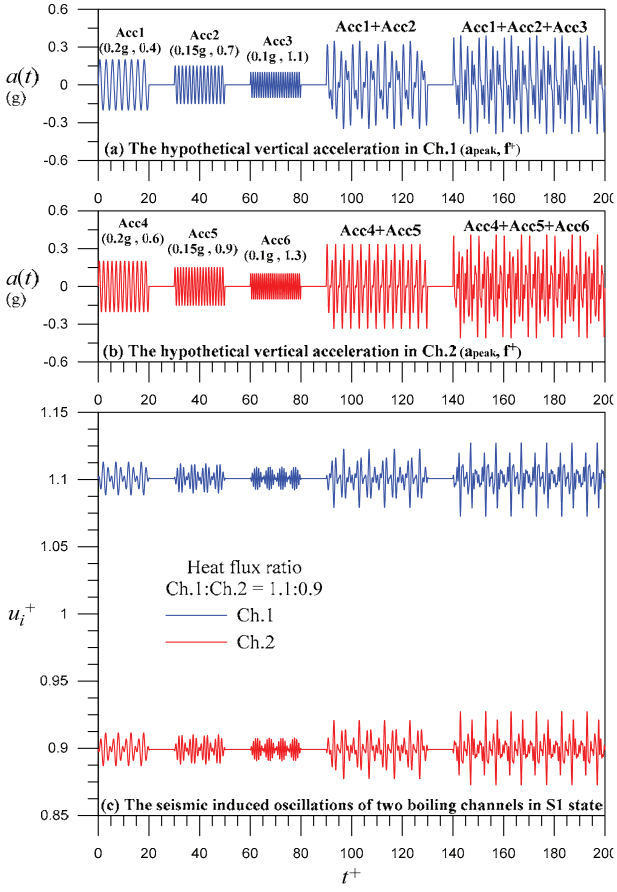

Figure 8. The Effect of Coupling Seismic Acceleration Waves with Different Amplitudes and Frequencies on the Transient Response of the S1 State.

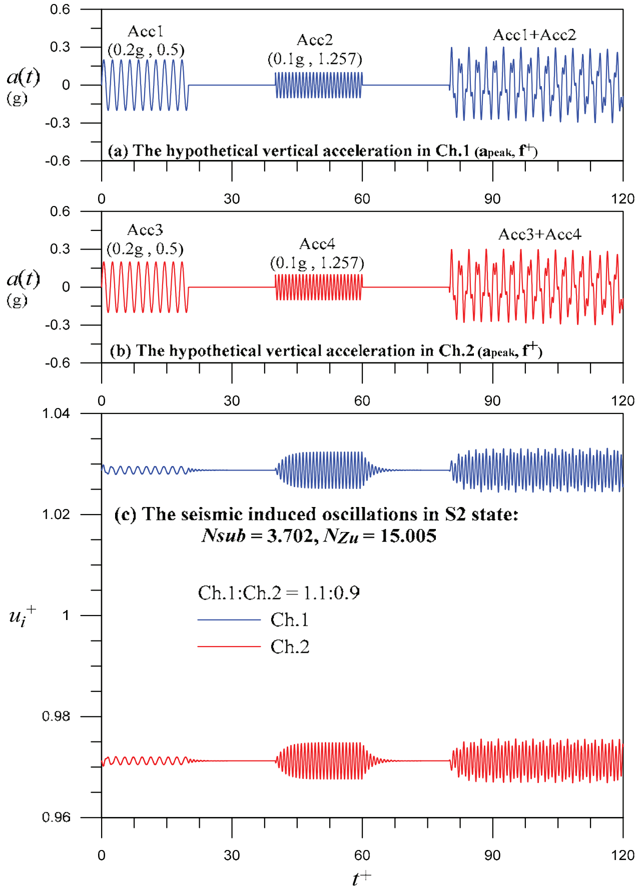

Figure 9. The Effect of Vertical Acceleration on the Transient Response of the S2 State.

The nature of vertical seismic vibration can be regarded as a composite of coupling sinusoidal waves with different amplitudes and frequencies. Figures 8(a) and 8(b) illustrate the hypothetical coupling set of vertical seismic accelerations, involving different peak amplitudes and frequencies, imposed on these two asymmetric heating channels, respectively. The transient responses caused by such coupling seismic waves are revealed in Fig. 8(c). The results indicate that more complex seismic induced oscillations could be triggered by the coupling set of seismic accelerations between channels. The more seismic-like oscillations would be caused by the hypothetical vertical accelerations consisting of more number of peak amplitudes and frequencies, as the induced oscillations between channels eventually shown in Fig. 8(c).

In contrast to the S1 state, the effect of vertical acceleration on the system behaviors is further performed in another stable state, i.e. S2 point shown in Fig. 3, with a higher power of N_{Zu}=15.005 and a higher inlet subcooling of N_{sub}=3.702. This stable state is more close to the stability boundary with respect to the normal operating state, i.e. S1 point, and is unrealistic where the reactor will scram. The natural frequency of the S2 state is about f^{+}=1.257. The hypothetical vertical accelerations between channels are supposed as revealed in Fig. 9(a) and 9(b), respectively, in which the frequency of smaller vertical accelerations imposed on each channel is set to the system's natural frequency. Figure 9 (c) displays the transient responses of the two boiling channels in the S2 state subject to these hypothetical vertical accelerations. The results indicate that the inlet velocity oscillations induced by the larger vertical accelerations, i.e. Acc1 and Acc3, are smaller by comparing with those caused by the smaller ones, i.e. Acc2 and Acc4. This demonstrates the larger amplitudes of resonance oscillations in the S2 state could be triggered by the smaller accelerations if their frequencies are equal to the system natural frequency. Moreover, by comparing the results between Fig. 4 for the S1 state and Fig. 9 for the S2 state, it suggests the strength of the resonance oscillation may depend on the stability degree of the initial state.

4.5 The impact of vertical acceleration on the pump trip condition

The results discussed before are based on the assumption of constant system flow rate during seismic motions and suggest that the effect of vertical acceleration on the cases studied may not be significant and depend on the stability degree of the initial states. However, the seismic vibration could generate different influences on the system, i.e. causing all the pumps trip, for which the system flow rate is never constant and presents natural circulation mode. In the pumps trip case, applying the boundary condition of the same and constant pressure drop among channels to instead the constant total flow rate under forced circulation mode at the steady states, while it will periodically oscillate with the vertical acceleration term (g_j*) during seismic transients. As a result, the modified equation for the inlet flow dynamics of channel 1 under natural circulation and seismic motion can be given as below:

$$\frac{du_{i,1}^{+}}{dt^{+}} = (\Delta P_0^{+} \times g_1^{*} - \Delta P_{H,1}^{+}) / M_{ch,1}^{+} \tag{21}$$

Where ΔP_0^{+} represents the steady state pressure drop under natural circulation without seismic motion while only considers the gravitational pressure head. Thus,

$$\Delta P_0^{+} = 1 / Fr \tag{22}$$

The steady state characteristics of such natural circulation parallel boiling channels depend on the heating power and inlet subcooling of reactor core as the other parameters are fixed and can be solved numerically using the subroutine SNSQE of Kahaner et al. [8]. The transient response of the pump trip case, by imposing vertical accelerations on the boiling channels during seismic motions, can be obtained using the subroutine SDRIV2 of Kahaner et al. [8].

The preliminary study on the pump trip condition caused by the seismic impact is evaluated in a natural circulation point of N_{sub}=0.665 and N_{Zu}=2.928, corresponding to 50% power and 32% flow rate of the normal operating state. The effect of external vertical vibration on such natural circulation state is performed by assuming the hypothetical vertical accelerations between channels as revealed in Fig. 10(a) and 10(b), respectively. Figure 10 (c) displays the transient responses of the two boiling channels with a heat flux ratio of 1.1:0.9 subject to these hypothetical vertical accelerations. The results indicate that the imposed vertical accelerations with a peak value of 0.1g could lead to very larger inlet velocity oscillations between channels under natural circulation (all pumps trip) compared with the results in Fig. 4 under normal forced circulation mode. This may be explained by the different degree of the vertical acceleration term, g_j*, in determining the channel pressure drop between the natural circulation and forced circulation modes. The pressure drop additionally contributed by seismic acceleration would possess a relatively small portion of channel pressure drop under normal operating state with 100% power and 100% flow rate, while would dominate a substantial portion under natural circulation state, i.e. 50% power and 32% flow rate. Therefore, the natural circulation system would be more susceptive to the impact of seismic acceleration. The very larger seismic induced oscillations could be triggered by the coupling effects of seismic accelerations and the thermal-hydraulic interactions between channels under the pumps trip condition, as shown in Fig. 10.

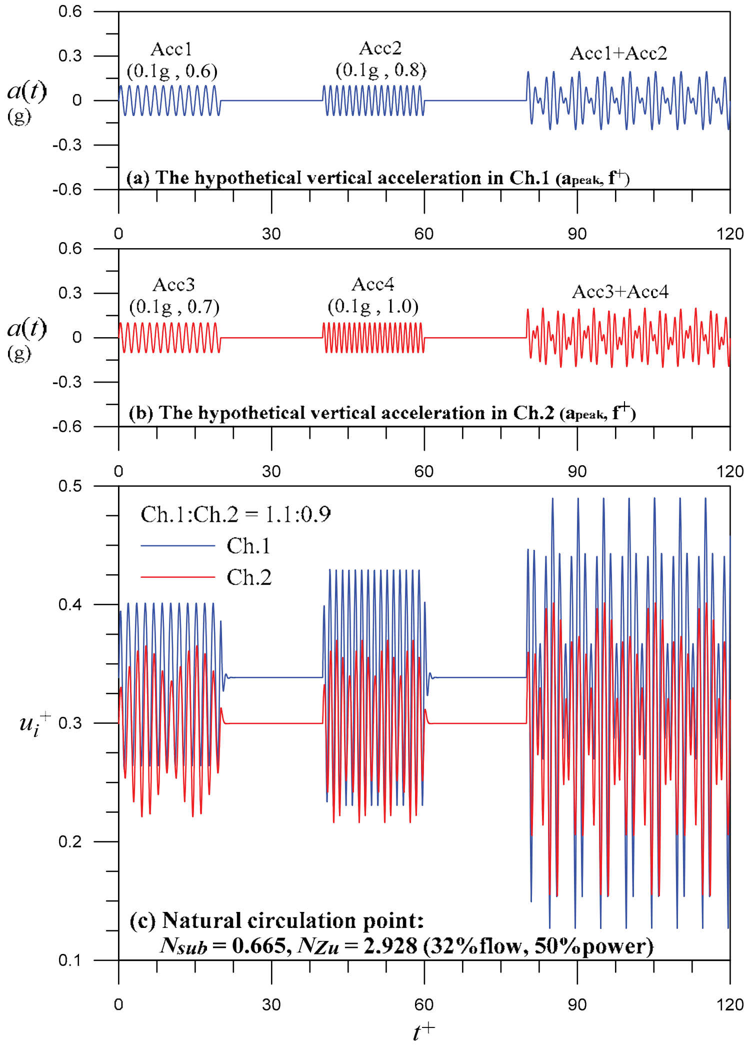

Figure 10. The Effect of Vertical Acceleration on the Transient Response of a Natural Circulation State, N_{sub}=0.665 and N_{Zu}=2.928.

5. CONCLUSIONS

This study investigates the effect of external vertical vibration on the system behaviors by adopting the multiple boiling channel model developed previously by the author incorporating with the external force method that only considers the vertical acceleration imposed by the seismic vibration. With the normal operating state of an ABWR as a reference case, the conclusions in this paper can be summarized as following:

- The effect of external vertical acceleration on the system transients may depend on their imposed amplitudes and frequencies.
- For the present asymmetric heating two channel system, increasing either of the inlet subcooling, outlet loss coefficient, channel length and power difference between channels would enhance the seismic induced oscillations.
- The effect of inlet loss coefficient on the seismic induced oscillation is consistent with the power/flow distribution between channels.
- The strengths of resonance oscillations caused by the seismic waves and the system natural oscillations may depend on the stability degree of the initial states under forced circulation mode.
- The coupling effect of vertical accelerations and channel interactions may cause very larger seismic induced oscillations in natural circulation case compared with that of the forced circulation system.

Further investigation in the effect of vertical acceleration on the system behaviors under natural circulation mode and their effects on the nuclear-coupled boiling system by introducing void-reactivity feedback will undergo in the near future.

NOMENCLATURE

a	acceleration (ms^{-2})
A_k	amplitude of the k-th wave
A_H	cross sectional area of the channel $\left(m^2\right)$
$A^+_{x-s,j}$	non-dimensional cross sectional area of the j-th heated channel, $= A_{H,j} / A_{H,1}$
C_{pf}	liquid constant pressure specific heat ($J\ K^{-1}kg^{-1}$)
D_H	diameter of the channel $\left(m\right)$
f	friction factor or frequency (s^{-1})
$f_{1\phi}$	single-phase friction factor
$f_{2\phi}$	two-phase friction factor
f^+	non-dimensional frequency,$=fL_H/u_s$
Fr	Froude number, $= u_s^2 / gL_H$
g	gravity acceleration (ms^{-2})
g^*	vertical acceleration term
h_f	saturated liquid enthalpy (Jkg^{-1})
h_{fg}	latent heat of evaporation (Jkg^{-1})
h_g	saturated vapor enthalpy (Jkg^{-1})
h_i	inlet liquid enthalpy $\left(Jkg^{-1}\right)$
H	vertical position of flow channel (m)
h^+	non-dimensional liquid enthalpy, $=(h-h_f)/h_s$
k	thermal conductivity $\left(Wm^{-1}K^{-1}\right)$ or loss coefficient
L	length $\left(m\right)$
L_H	channel length $\left(m\right)$
L^+	non-dimensional length, $= L / L_H$
M	mass $\left(kg\right)$
M^+	non-dimensional mass, $=M/\rho_f L_H A_H$
N_s	number of nodes in the single-phase region
N_{exp}	thermal expansion number, $= \beta h_{fg} \upsilon_f / C_{pf} \upsilon_{fg}$
N_{Zu}	average steady-state Zuber (phase change) number
$N_{Zu,j}$	steady-state Zuber number for j-th channel, $=Q_{j0}/(\rho_f A_{H,j} u_s h_{fg}) \times \upsilon_{fg}/\upsilon_f$
N_{sub}	subcooling number, $=(h_f-h_i)/h_{fg} \times \upsilon_{fg}/\upsilon_f$
P	system pressure (bar)
Q_j	steady-state heating power in j-th channel (W)
q''	heat flux $\left(Wm^{-2}\right)$
q_0	steady state heat flux $\left(Wm^{-2}\right)$
q''^+	non-dimensional heat flux, $= q'' / q_0''$
t	time $\left(s\right)$
t^+	non-dimensional time, $= t\, u_s / L_H$

u	velocity $\left(ms^{-1}\right)$
u_{i0}	steady state inlet velocity $\left(ms^{-1}\right)$
u_s	velocity scale, $=u_{i0}$
u^+	non-dimensional velocity, $=u/u_s$
υ_f	specific volume of saturated liquid $\left(m^3kg^{-1}\right)$
υ_{fg}	difference in specific volume of saturated liquid and vapor $\left(m^3kg^{-1}\right)$
x_e	exit quality
z	axial coordinate $\left(m\right)$
z^+	non-dimensional axial coordinate, $=z/L_H$

Greek symbols

α	void fraction or thermal diffusivity
ϕ	phase
ΔP	pressure drop $\left(Pa\right)$
ΔP^+	non-dimensional pressure drop, $=\Delta P/\rho_f u_s^2$
δx	$(x-x_0)$ for variable x, x_0 represents the steady-state value
ρ	density $\left(kgm^{-3}\right)$
ρ^+	non-dimensional density, $=\rho/\rho_f$
ρ_f	density of saturated liquid $\left(kgm^{-3}\right)$
$\Lambda_{1\phi}$	single-phase friction number, $=f_{1\phi}L/2D$
$\Lambda_{2\phi}$	two-phase friction number, $=f_{2\phi}L/2D$
λ	boiling boundary $\left(m\right)$
λ^+	non-dimensional boiling boundary, λ/L_H

Subscripts

ch	channel
e	exit of the channel
H	heated channel
i	inlet of the channel
j	j-th channel
n	n-th node in the single-phase region
0	steady state

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REFERENCES

1. J. A. Boure, A. E. Bergles and L. S. Tong, "Review of Two-Phase Flow Instability," *Nuclear Engineering and Design* **25**, pp.165–192 (1973).
2. Earthquake Lab, "Introduction to Earthquake Waves", http://www.eq.ccu.edu.tw / ~ccusgm/ seismography.htm (2004).
3. M. Hirano and T. Tamakoshi, "An Analytical Study on Excitation of Nuclear-Coupled Thermal Hydraulic Instability Due to Seismically Induced Resonance in BWR," *Nuclear Engineering and Design* **162**, pp. 307–315 (1996).
4. A. Satou, T. Watanabe, Y. Maruyama and H. Nakamura, "Neutron-Coupled Thermal Hydraulic Calculation of BWR under Seismic Acceleration," *Progress in Nuclear Science and Technology*, **Vol. 2**, pp.120-124 (2011).
5. T. Watanabe, "On the Numerical Approach for Simulating Reactor Thermal Hydraulics under Seismic Conditions," *Annals of Nuclear Energy* **49**, pp. 200–206 (2012).
6. J. D. Lee and C. Pan, "Dynamics of Multiple Parallel Boiling Channel Systems with Forced Flows," *Nuclear Engineering and Design* **192**, pp. 31-44 (1999).
7. A. Clausse and R.T. Jr. Lahey, "An Investigation of Periodic and Strange Attractors in Boiling Flows Using Chaos Theory," *Proceedings of the Ninth International Heat Transfer Conference*, Jerusalem, vol. 2, pp. 3-8 (1990).
8. D. Kahaner, C. Moler and S. Nash, "Numerical Methods and Software, Prentice Hall," (1989).
9. Y. Guo, J. Huang, G. Xia and H. Zeng, "Experiment investigation on Two-Phase Flow Instability in a Parallel Twin-Channel System," *Annals of Nuclear Energy* **37**, pp. 1281-1289 (2010).
10. Taiwan Power Company, "Preliminary Safety Analysis Report: Lungmen Nuclear Power Station Units 1 & 2," Taipei, Taiwan (1997).