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The influence of void-reactivity feedback on the bifurcation phenomena and nonlinear characteristics of a single nuclear-coupled boiling channel

Jin-Der Lee [a,*], Yuh-Ger Lin [b], Shao-Wen Chen [b], Chin Pan [b]

[a] Nuclear Science and Technology Development Center, National Tsing Hua University, 101, Sec. 2, Kuangfu Rd., Hsinchu 30013, Taiwan, ROC
[b] Department of Engineering and System Science and Institute of Nuclear Engineering and Science, National Tsing Hua University, 101, Sec. 2, Kuangfu Rd., Hsinchu 30013, Taiwan, ROC

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ABSTRACT

This study employs the nonlinear dynamic model developed previously by the authors to investigate the effect of void-reactivity feedback on the bifurcation phenomena and nonlinear characteristics of a single nuclear-coupled boiling channel in an advanced boiling water reactor. The parametric effects on the system stability are evaluated by nonlinear analyses as well. The effects of void-reactivity feedback and outlet flow resistance will both destabilize the system, while the inlet flow resistance will generate a stable effect on the system. The strength of void-reactivity feedback has a great influence on the bifurcation phenomena and nonlinear dynamics of the single nuclear-coupled boiling channel. The system can evolve from stable state, limit cycle, periodic to chaotic oscillation through supercritical Hopf and period-doubled bifurcations as the increase in the absolute value of void-reactivity coefficient. In addition, the system can experience a series of period-doubled bifurcation to present various types of oscillations, from periodic ones to chaos, in the unstable region as the controlling parameter of steady phase change number or subcooling number under some specific conditions with a relatively strong void-reactivity coefficient of $C_\alpha = -0.38\$/\%$. The appearance of a periodic cycle of three suggests that there may be immeasurable periodic types of nonlinear oscillations in the limited unstable space of this system.

1. Introduction

Density wave oscillations (DWOs) are a typical type of dynamic instability occurring in the boiling system (Boure et al., 1973). 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. Because of the strong coupling between the thermal–hydraulics and the neutronics, the issue of nuclear-coupled thermal–hydraulic instability is of significant important for the design, operation and safety of boiling water reactors (BWRs) and advanced boiling water reactors (ABWRs).

The coupling nonlinear interactions and feedbacks among the channel thermal–hydraulics, fuel rod heat transfer and neutron field dynamics are characteristic in a nuclear boiling system. The void-reactivity feedback is one of important parameters to affect the stability characteristics and nonlinear dynamics of such a system. Some experimental facilities were designed to investigate the void-reactivity feedback on the system stability, such as for natural circulation BWRs (Kuran et al., 2004; Ishii et al., 2006) and for natural circulation integral modular water reactor (Dixit et al., 2013). Ishii et al. (2006) reported that the presence of the void-reactivity coupling had a major destabilizing effect on the flashing-induced loop type oscillations. Dixit et al. (2013) revealed that Type-I DWOs were observed experimentally during the start-up procedure at very low pressure of a natural circulation experimental loop with and without void-reactivity feedback, however, the impact of void-reactivity feedback on the system stability was insignificant in their startup experiments. On the other hand, the void-reactivity feedback on the system stability was extensively studied by theoretical analyses. The destabilizing effects on the type-II DWOs in the high power area have been reported in the nuclear systems of single boiling channel (Van Bragt and van der Hagen, 1998; Lin et al., 1998; Lee and Pan, 2005a; Durga Prasad and Pandey, 2008) or multiple boiling channels (Lee and Pan, 2005b, 2014; Lee et al., 2015; Durga Prasad and Pandey, 2010), either under forced circulation boiling (Lin et al., 1998; Lee and Pan, 2005b, 2014) or natural circulation boiling conditions (Van Bragt and van der Hagen, 1998; Lee and Pan, 2005a; Lee et al., 2015; Durga Prasad and Pandey, 2008, 2010).

Some nonlinear bifurcation phenomena in the unstable region, such as subcritical and supercritical Hopf bifurcations, could appear in two-phase flow systems (Rizwan-uddin and Dorning,

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[*] Corresponding author.
E-mail address: ctlee2@mx.nthu.edu.tw (J.-D. Lee).

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Nomenclature

A	area (m^2)
A_H	cross sectional area of the channel (m^2)
C	dynamic precursor concentration (#m^{-3})
C_0	steady state precursor concentration (#m^{-3})
C^+	non-dimensional precursor concentration, $= (C - C_0)/C_0$
C_{pf}	liquid constant pressure specific heat (J kg^{-1} K^{-1})
C_α	void-reactivity coefficient ($\$/\%$)
D_H	diameter of the channel (m)
f	friction factor
$f_{1\phi}$	single-phase friction factor
$f_{2\phi}$	two-phase friction factor
Fr	Froude number, $= u_s^2/gL_H$
g	gravity acceleration (m s^{-2})
h	enthalpy (J kg^{-1})or heat transfer coefficient (Wm^{-2} K^{-1})
h_C	clad-to-coolant heat transfer coefficient (Wm^{-2} K^{-1})
h_{gap}	Pellet-to-clad gap conductance (Wm^{-2} K^{-1})
h_f	saturated liquid enthalpy (J kg^{-1})
h_{fg}	latent heat of evaporation (J kg^{-1})
h_g	saturated vapor enthalpy (J kg^{-1})
h_i	inlet liquid enthalpy (J kg^{-1})
h^+	non-dimensional enthalpy, $= (h - h_f)/h_f$
k	thermal conductivity (Wm^{-1} K^{-1})or loss coefficient
L	length (m)
L_H	channel length (m)
L^+	non-dimensional length, $= L/L_H$
M	mass (kg)
M^+	non-dimensional mass, $= M/\rho_f A_H L_H$
N	dynamic neutron density (#m^{-3})
N_0	steady state neutron density (#m^{-3})
N^+	non-dimensional neutron density, $= (N - N_0)/N_0$
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_{pch}	dynamic phase change number, $= \frac{Q}{\rho_f A_H u_s}\frac{\upsilon_{fg}}{h_{fg}\upsilon_f}$
N_{pch0}	steady phase change number, $= \frac{Q_0}{\rho_f A_H u_s}\frac{\upsilon_{fg}}{h_{fg}\upsilon_f}$
N_{sub}	subcooling number, $= \frac{h_f - h_i}{h_{fg}}\frac{\upsilon_{fg}}{\upsilon_f}$
P	system pressure (bar)
Q	heating power (W)
q''	heat flux (Wm^{-2})
q''_0	steady state heat flux (Wm^{-2})
q''^+	non-dimensional heat flux, $= q''/q''_0$
q'''	volumetric heat generation rate (Wm^{-3})
r	radius (m)
T	temperature (K)
T_0	steady-state heated wall temperature
T_{sat}	saturation temperature (K)
T^+	non-dimensional temperature, $= (T - T_0)/T_{sat}$
t	time (s)
t_{ref}	time scale, $= L_H/u_s$
t^+	non-dimensional time, $= t/t_{ref}$
u	velocity (ms^{-1})
u_{i0}	steady state inlet velocity (ms^{-1})
u_s	velocity scale, $= u_{i0}$
u^+	non-dimensional velocity, $= u/u_s$
υ_f	specific volume of saturated liquid (m^3 kg^{-1})
υ_{fg}	difference in specific volume of saturated liquid and vapor (m^3kg^{-1})
x_e	exit quality
z	axial coordinate (m)
z^+	non-dimensional axial coordinate, $= z/L_H$

Greek symbols

α	void fraction
β	delayed neutron fraction or thermal expansion coefficient
ΔP	pressure drop (Pa)
ΔP^+	non-dimensional pressure drop, $= \Delta P/\rho_f u_s^2$
ρ	density (kg m^{-3})
ρ_f	density of saturated liquid (kg m^{-3})
ρ^+	non-dimensional density, $= \rho/\rho_f$
φ	reactivity ($\Delta K/K$, where K is multiplication factor)
Λ	neutron generation time (s)
$\Lambda_{1\phi}$	single-phase friction number, $=f_{1\phi}L_H/2D_H$
$\Lambda_{2\phi}$	two-phase friction number, $=f_{2\phi}L_H/2D_H$
λ	boiling boundary (m)
λ^+	non-dimensional boiling boundary, $=\lambda/L_H$
λ_C	decay constant of delayed neutron precursor (s^{-1})

Subscripts

ch	channel
e	exit of the channel
i	inlet of the channel
n	n-th node in the single-phase region
0	steady state
H	heated channel
F	fuel pellet
C	cladding

1986; Paul and Singh, 2014). Period-N limit cycle oscillation and chaotic oscillation might occur in the unstable region of a two-phase flow system with periodically oscillating pressure drop (Rizwan-uddin and Dorning, 1988). In addition, as a result of the strong coupling nonlinear interactions and feedbacks among the channel thermal–hydraulics, fuel rod heat transfer and neutron field dynamics, complex nonlinear phenomena may exist in various nuclear-coupled boiling systems. March-Leuba et al. (1986) suggested that the reactivity instability was dominated by the void-reactivity feedback. The nuclear boiling system could experience periodic toward chaotic oscillations through a cascade of period-doubled bifurcations when the neutronic feedback gain exceeded a certain critical value. With the bifurcation parameter set to the critical value, the limit cycle oscillation was verified through a hybrid reactor/simulation test (Turso et al., 1995). Bindra and Rizwan-uddin (2014) also suggested that stable limit cycle oscillation, i.e. the existence of supercritical Hopf bifurcation, could present in the unstable region near the stability boundary. Lin et al. (1998) illustrated a series of period-doubled bifurcation at high inlet subcoolings in an autonomous nuclear-coupled boiling system. Eventually chaotic oscillations appeared in their forced circulation system. Recently, Lee and Pan (2005a) recognized a route from periodic toward chaotic oscillation through period-doubled bifurcation for a nuclear-coupled boiling natural circulation loop with a strong void-reactivity feedback. Durga Prasad and Pandey (2008) also reported such a route to chaos through period-doubled bifurcation in a nuclear-coupled natural circulation system.

The multiple coupling interactions and feedbacks among multi-channel thermal–hydraulics, fuel rod heat transfer and multi-point neutron field dynamics can induce complex nonlinear phenomena in a parallel nuclear-coupled boiling channels system. Complex periodic types of oscillation and a distinctive type of complex chaotic attractor could be identified in the multiple nuclear-coupled boiling channels system with a multi-point reactor in some specific operating conditions, either under forced circulation boiling

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