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Nonlinear dynamic analysis of a two-phase natural circulation loop with multiple nuclear-coupled boiling channels

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A B S T R A C T

This study integrates the models developed previously by the authors to explore the stabilities, nonlinear dynamics and oscillation modes of a two-phase natural circulation loop with multiple nuclear-coupled boiling channels. The results indicate that both the pure thermal-hydraulic and nuclear-coupled boiling systems indeed have two instability regions, i.e. type-I and type-II instabilities, respectively. The pure thermal-hydraulic system tends to present in-phase mode of oscillations at the type-I boundary states and, in general, out-of-phase oscillations along with the type-II stability boundary. The oscillation modes may be affected by the configuration of parallel channels. By introducing the void-reactivity feedback together with neutron interaction, the coupling thermal-hydraulic and nuclear effects would induce complex influences on the system stability as well as the nonlinear oscillation modes. The in-phase mode, instead of out-of-phase mode, majorly dominates over the type-II boundary as the neutronic feedback is increased through void-reactivity coefficient. The complex nonlinear phenomena, such as complex periodic and chaotic oscillations, may appear in this multi-channel nuclear-coupled boiling natural circulation loop subject to a strong void-reactivity feedback ($3C\alpha$) coupled with a weak subcore-to-subcore neutron interaction ($\varepsilon_{ij} = 7.0$).

1. Introduction

Many advanced designs benefiting from the experience accumulated with the current plants are adopted by the advance boiling water reactors (ABWRs). Natural circulation is an important passive heat removal mechanism for an ABWR during the startup and shutdown processes. The boiling natural circulation system may be susceptible to different types of instability, i.e. static and dynamic instabilities. Density wave oscillations (DWOs) are a typical type of dynamic instability occurring in the boiling system (Boure et al., 1973). The stability issues of DWOs in two-phase natural circulation systems are very crucial to their safe operations.

Most two-phase flow systems 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. Guido et al. (1991) indicated that in-phase and out-of-phase oscillations were the fundamental oscillation modes for an identical double channel system. Podowski et al. (1990) revealed complex interaction modes involving coupled parallel channels caused by the differences among the channels. Lee and Pan (1999) reported that complex channel-to-channel interactions might drive the system more unstable with increasing number of channels. The oscillations among channels were essentially out-of-phase in the multi-channel system having a constant force circulation flow rate. This meant that out-of-phase instability could appear in such a system. Moreover, the out-of-phase oscillations could be identified in a parallel twin-channel experimental system with uniform and non-uniform heating powers at given flow rates (Guo et al., 2010). Xia et al. (2012) observed that four types of instability, i.e. Ledinegg instability, Ledinegg inducing out-of-phase instability, in-phase and out-of-phase instabilities, might exist in a relative low-pressure parallel narrow multi-channel system.

A natural circulation loop has two major types of instability (Fukuda and Kobori, 1979), i.e. type-I instability in the low power region caused by the gravitational pressure drop and type-II instability in the high power region dominated by the two-phase frictional pressure drop. In a natural circulation system, the system flow rate will depend on the system geometries and the operating parameters, such as the heating power and inlet subcooling. The nonlinear oscillation modes among parallel channels could be

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Nomenclature

A	area (m^2)
A_H	total cross sectional area of multiple heated channels (m^2)
$A_{H,j}$	cross sectional area of the *j*-th heated channel (m^2)
C_j	dynamic precursor concentration in j-th subcore ($\#m^{-3}$)
C_{j0}	steady state precursor concentration in j-th subcore ($\#m^{-3}$)
C_j^+	non-dimensional precursor concentration in j-th subcore, $=(C_j - C_{j0})/C_{j0}$
C_D	Doppler-reactivity coefficient ($\$/\Delta T_F$)
C_{pf}	liquid constant pressure specific heat ($J\ kg^{-1}\ K^{-1}$)
C_α	void-reactivity coefficient ($/%)
D	diameter (m)
f	friction factor
$f_{1\phi}$	single-phase friction factor
$f_{2\phi}$	two-phase friction factor
Fr	Froude number, $=u_s^2/gL_H$
H_{jm}	interaction coefficient between subcores
h	heat transfer coefficient ($W\ m^{-2}\ K^{-1}$) or enthalpy ($J\ kg^{-1}$)
h_c	clad-to-coolant heat transfer coefficient ($W\ m^{-2}\ K^{-1}$)
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_{gap}	Pellet-to-clad gap conductance ($W\ m^{-2}\ K^{-1}$)
h_i	inlet liquid enthalpy ($J\ kg^{-1}$)
h_s	enthalpy scale, $=Q_0/\rho_f A_H u_s$
h^+	non-dimensional liquid enthalpy, $=(h-h_f)/h_s$
k	thermal conductivity($W\ m^{-1}\ K^{-1}$) 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, $=M/\rho_f L_H A_H$
N_j	dynamic neutron density in j-th subcore ($\#m^{-3}$)
N_{j0}	steady state neutron density in j-th subcore ($\#m^{-3}$)
N_R	number of nodes in the riser
N_s	number of nodes in the single-phase region of the heated channel
N_{pch}	average steady-state phase change number
$N_{pch,j}$	steady-state phase change 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, $=(h_f-h_i)/h_{fg}\times\upsilon_{fg}/\upsilon_f$
N_j^+	non-dimensional neutron density in j-th subcore, $=(N_j - N_{j0})/N_{j0}$
P	system pressure (bar)
Q_j	heating power in j-th channel (W)
Q_{j0}	steady-state heating power in j-th channel (W)
Q_0	average steady-state heating power (W)
q''	heat flux ($W\ m^{-2}$)
q''_0	steady state heat flux ($W\ m^{-2}$)
q''^+	non-dimensional heat flux, $= q''/q''_0$
q'''	volumetric heat generation rate ($W\ m^{-3}$)
r	radius (m)
Re	Reynolds number, $=uD/\nu$
T	temperature (K)
T_0	steady-state heated wall temperature (K)
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 ($m\ s^{-1}$)
u_{i0}	steady state inlet velocity ($m\ s^{-1}$)
u_s	velocity scale, $= 1.62 g^{0.569} D_H^{0.705} \upsilon^{-0.137}$ (Jeng and Pan, 1994)
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 ($m^3\ kg^{-1}$)
V	volume (m^3)
W	mass flow rate ($kg\ s^{-1}$)
W^+	non-dimensional mass flow rate, $= W/\rho_f A_H u_s$
x	quality
z	axial coordinate (m)
z^+	non-dimensional axial coordinate, $=z/L_H$

Greek symbols

α	void fraction or thermal diffusivity
β	delayed neutron fraction
ε_{jm}	neutron interaction parameter between subcores
ν	kinematic viscosity (m^2/s)
ΔP	pressure drop (Pa)
ΔP^+	non-dimensional pressure drop, $=\Delta P/\rho_f g L_H$
δx	$(x - x_0)$ for variable x, x_0 represents the steady-state value
ρ	density ($kg\ m^{-3}$) or reactivity ($\Delta K/K$, where K is multiplication factor)
ρ^+	non-dimensional density, $=\rho/\rho_f$
ρ_f	density of saturated liquid ($kg\ m^{-3}$)
Λ	friction number or neutron generation time (s)
$\Lambda_{1\phi}$	single-phase friction number, $=f_{1\phi}L/2D$
$\Lambda_{2\phi}$	two-phase friction number, $=f_{2\phi}L/2D$
λ	boiling boundary (m)
λ^+	non-dimensional boiling boundary, $= \lambda/L_H$
λ_C	decay constant of delayed neutron precursor (s^{-1})

Subscripts

ch	channel
C	cladding
e	exit of heated channel
ex	exit
f	saturated liquid
fw	feedwater
F	fuel pellet
g	saturated vapor
H	heated channel
i	inlet of heated channel
in	inlet
ld	lower downcomer
lp	lower plenum
mix	mixed flow
j	*j*-th channel or subcore
n	*n*-th node in the single-phase region
r	*r*-th node in the riser
R	riser
sep	steam separator
tot	total
ud	upper downcomer
up	upper plenum
1ϕ	single-phase
2ϕ	two-phase
0	steady state

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