Annals of Nuclear Energy 112 (2018) 289–306

Contents lists available at ScienceDirect

Annals of Nuclear Energy

journal homepage: www.elsevier.com/locate/anucene

A methodology to investigate the effect of vertical seismic acceleration on the qualitative dynamic behaviors of a natural circulation loop with parallel nuclear-coupled boiling channels

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ARTICLE INFO

Article history:
Received 28 April 2017
Received in revised form 16 August 2017
Accepted 5 October 2017

Keywords:
Natural circulation
Parallel boiling channels
Void-reactivity feedback
Seismic acceleration

ABSTRACT

By adopting the external force method to consider the impact of seismic vibration on the two-phase flow system, this study integrates the nonlinear dynamic model of a nuclear-coupled boiling parallel-channel natural circulation loop (NCL) developed previously by the authors with the external vertical seismic accelerations to investigate the qualitative dynamic behaviors of the seismic-induced oscillations in the NCL. The methodology employed in this study could simulate a real vertical seismic acceleration and address the major nonlinear characteristics of seismic-induced oscillations by the comparisons between the results caused by the real vertical seismic acceleration and the simulated wave. The seismic-induced oscillations are found to be highly consistent with the resonance effect in different natural circulation stable states. The resonance part of the seismic waves would dominate the nonlinear phenomena of the system under vertical seismic accelerations imposed. The vertical seismic motion could cause in-phase mode of oscillation among boiling channels in this NCL system. In addition, some parametric effects on the seismic-induced oscillations are performed in the present NCL system. The natural circulation system with a higher subcooling may trigger a more prominent resonance phenomenon, due to the inherent stability characteristics of the initial states, and thus lead to a more dramatic seismic-induced oscillation in the cases studied.

1. Introduction

The seismic issue is very important for the design, operation and safety of nuclear power plants. The seismic vibration is usually inaudible with a low frequency less than 20 Hz, ranged from 0.1 Hz to tens of Hz (USGS, 2014). 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 seismic excitation tests of multiple fuel assemblies indicated that the maximum displacement of the fuel assemblies at both ends of the row could reach about the order of 10 mm (Mitsubishi Heavy Industries, 2008). To simulate the seismic vibration conditions, the study should involve the major vibration characteristics, including vibration frequency and peak amplitude.

The external vibrations, such as seismic motions, may cause all the pumps trip. If no scram function is inserted, the advanced boiling water reactors (ABWRs) would operate in natural circulation boiling condition in the absence of reactor internal pump operation. The natural circulation boiling system is generally more susceptible to distinct 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). A natural circulation loop (NCL) has two major types of DWO 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. Therefore, the stability issues of DWOs coupled with the impact of seismic vibration in two-phase natural circulation systems, i.e. ABWR, should be very crucial to their safe operations.

Most two-phase flow systems involve parallel boiling channels, which channel-to-channel interactions can distribute over the channels. The studies concerning DWO combined with parallel

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https://doi.org/10.1016/j.anucene.2017.10.009
0306-4549/

Nomenclature

a	acceleration (ms^{-2})
a_{peak}	peak acceleration, = $-a_{max}g$ (ms^{-2})
a_{max}	non-dimensional peak magnitude
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 or frequency (Hz)
$f_{1\phi}$	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 parameter
H_{jm}	interaction coefficient between subcores
h	heat transfer coefficient (Wm^{-2} K^{-1}) or enthalpy (Jkg^{-1})
h_c	clad-to-coolant heat transfer coefficient (Wm^{-2} K^{-1})
h_f	saturated liquid enthalpy (Jkg^{-1})
h_{fg}	latent heat of evaporation (Jkg^{-1})
h_g	saturated vapor enthalpy (Jkg^{-1})
h_{gap}	Pellet-to-clad gap conductance (Wm^{-2} K^{-1})
h_i	inlet liquid enthalpy (Jkg^{-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 (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, $=M/\rho_f L_H A_H$
$N_{\exp}$	thermal expansion number, $= \beta h_{fg}\upsilon_f/C_{pf}\upsilon_{fg}$
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_{pch0}	average steady-state phase change number
$N_{pch0,j}$	steady phase change number for j-th channel, $=Q_{j0}\upsilon_{fg}/A_{H,j}u_s h_{fg}$
$N_{pch,j}$	dynamic phase change number for j-th channel, $=Q_j\upsilon_{fg}/A_{H,j}u_s h_{fg}$
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*)
PSD_k	power spectrum density of the k-th frequency (dB)
PSD_k^+	peak strength of the k-th frequency wave relative to the maximum peak amplitude, $=PSD_k/PSD_{max}$
Q_j	heating power in j-th channel (W)
Q_{j0}	steady-state heating power in j-th channel (W)
Q_0	steady-state heating power (W)
q''	dynamic heat flux (Wm^{-2})
q''_0	steady state heat flux (Wm^{-2})
q''^+	non-dimensional dynamic heat flux, $=q''/q''_0$
q'''	volumetric heat generation rate (Wm^{-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 (ms^{-1})
u_i	inlet velocity (ms^{-1})
u_s	velocity scale, $= 1.62g^{0.569}D_H^{0.705}\nu^{-0.137}$ (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 or thermal expansion coefficient
ε_{jm}	neutron interaction parameter between subcores
ν	kinematic viscosity (m^2/s)
ΔP	pressure drop (Pa)
ΔP^+	non-dimensional pressure drop, $=\Delta P/\rho_f g L_H$
ρ	density (kg m^{-3})
ρ^+	non-dimensional density, $=\rho/\rho_f$
ρ_f	density of saturated liquid (kgm^{-3})
φ	reactivity ($\Delta K/K$, where K is multiplication factor)
ϕ	phase angle (rad)
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
k	k-th external acceleration wave
n	n-th node in the single-phase region
r	r-th node in the riser
R	riser
sep	steam separator