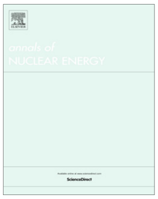
Annals of Nuclear Energy 111 (2018) 262–270

Contents lists available at ScienceDirect

Annals of Nuclear Energy

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



Investigation of the density wave oscillation in ocean motions with reduced order models

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ARTICLE INFO

Article history:
Received 19 April 2017
Received in revised form 8 September 2017
Accepted 11 September 2017

Keywords:
Ocean motion
Density wave oscillation
Two phase flow
Phase change number

ABSTRACT

The two phase flow instability is an important phenomenon in nuclear power and thermal systems. In the research and design of small modular reactor, the effect of ocean motions on the two phase flow instability should be evaluated. In this work, the density wave oscillation in a uniformly heated channel in ocean motions is investigated with reduced order model by transforming the partial differential equations to ordinary differential equations. This kind of frequency domain method is complementary to the time domain analysis with system codes, not as alternatives. The parameter about the degree of instability is defined for the quantitative analysis of two phase flow instability. The results are in satisfactory agreement with experimental results. The effect of ocean motions on density wave oscillation in a uniformly heated channel is analyzed quantitatively. The parametric study is also carried out.

1. Introduction

The phenomenon of two-phase flow instability occurred widely in many industrial systems and facilities, such as nuclear reactor steam generators, turbo-machinery, and two phase flow heat exchangers etc (Kakac and Cao, 2009). It could cause mechanical vibration, reduce critical heat flux (CHF) and bring some control and safety problems. Therefore, the analysis of two-phase flow instability is very important for the safety of nuclear reactors and two-phase flow systems.

The most important instability for two phase flow systems operating in high pressure condition is Density Wave Oscillation (DWO). The DWO is caused by a perturbation in the inlet flow rate and then change the two phase mass quality and the mixture density. This perturbation creates a disturbance in the local pressure drop which may intensify the flow rate perturbation in unstable region. This kind of self-amplified thermal hydraulic feedback results in the DWO finally (Uddin, 1994). The operating pressures for many engineering systems are very high.

Since only the DWO instability is observed at high pressures, it attracted the attention of many scholars. Clausse and Lahey (1990) introduced a lumped parameter model for the nonlinear analysis of autonomous DWO in single channel. This model was developed based on a Galerkin nodal approximation for a boiling channel. Karve (1998) used quadratic approximations to analyze the single phase enthalpy and two-phase quality with homogeneous equilibrium model (HEM). This model could reduce the order of the systems as set of coupled nonlinear ordinary differential equations (ODEs) which were useful in the bifurcation analysis. Dokhane (2004) developed a reduced order model to simulate the different types of instabilities encountered in heated channels and BWRs, viz. density wave oscillations (DWOs), as well as in-phase and out-of-phase oscillations in the reactor core. His results revealed that both sub and supercritical Hopf bifurcations were observed along the stability boundary. Chang et al. (1997) found that a boiling channel with riser may experience chaotic oscillations, while the system without riser underwent a supercritical bifurcation. They also observed a limit cycle instead of chaos subjected to a constant pressure drop. The result of Karve (1998) was in agreement with the experimental data of Kyung and Lee (1994). Durga and Pandey (2008) investigated the stability and non-linear dynamics of a natural circulation boiling loop with a lumped parameter model. They observed chaotic oscillations under strong reactivity feedback in the Type-II region in boiling channels. Therefore, they suggested that the presence of riser aggravated chaotic oscillations. Uddin (2006) conducted a semi-analytical bifurcation analysis using BIFDD code with non-linear model. Mishra and Singh (2016) conducted linear stability analysis for two-phase flow in inclined channels with reduced order models. They carried out bifurcation analysis to capture the non-linear dynamics and to identify the regions in parameter space. The subcritical and supercritical bifurcations were also analyzed. It is found that the stability characteristics of two-phase flow in horizontal and inclined

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http://dx.doi.org/10.1016/j.anucene.2017.09.016

Nomenclature

a	phase variable for single phase enthalpy
D	channel diameter
g	gravitational acceleration
Fr	Froude number
h	coolant enthalpy
Δh_{fg}	latent heat
k	loss coefficient
L	channel length
N_f	Friction number
N_{pch}	phase change number
N_{sub}	subcooling number
ΔP	pressure drop
q_w	heat flux
s	phase variable for two phase quality
u	velocity
x	vapor quality

Greek letters

ε	perimeter
μ	onset of boiling
ρ	density

Superscripts

$-$	dimensionless parameter

Subscripts

1ϕ	single phase
2ϕ	two phase
acc	acceleration
$exit$	channel exit
ext	external
f	liquid
g	vapor
m	mixture
r	reference

channels were significantly different from those of vertical channels even in the same operating conditions. Their analysis also revealed that the dynamics in inclined and horizontal channels were different because of the variation of gravitational pressure drop.

Recently, the development of advanced small modular reactor (SMR) has been accelerated in many countries (Li et al., 2013). SMRs are of particular interest for both near-term and advanced future non-electrical applications (Jurewicz, 2015). The SMR could be built in land or on a floating platform in the sea. It is known that several SMRs are going to be built on floating platforms in China (Yan and Wen, 2015; Yan, 2017). In ocean motions, including heaving, rolling and pitching motions shown in Fig. 1, the flow and heat transfer is different from that in land due to the effect of ocean waves. The coupling of two phase flow instability with ocean motions might result in complex nonlinear phenomenon.

Tan et al. (2009) carried out experiments for the DWO in rolling motion and found that the stability boundary in case of complex flow oscillation was similar to that of density wave oscillation in stationary state in specific experimental cases. The impact of rolling parameters on the stability boundary was not significant. Tang et al. (2014) suggested that the flow oscillation in ocean motions was a superposition of thermal-induced oscillation and motion-induced oscillation. It was found that the difference of boundary heat flux induced by ocean motions was no more than ±5% through the comparison of experiments in stationary state and ocean motions in their experimental cases. The instability was mainly affected by thermal parameters.

The above mentioned experiments were mainly carried out in low pressure cases and some specific motion conditions. These authors did not give a clear picture about the stability boundary in ocean motions. Guo et al. (2008) developed the models for the two phase flow instability between multi-channels in ocean motions. They investigated the instability oscillating trajectories in a multi-channel system and found that some of the trajectories show chaotic characteristics. Then they analyzed the curve of mass flow rate with Fast Fourier Transformation (FFT) method and analyzed the onset of parallel-channel instability (Guo et al., 2010). Based on these researches, Zhang et al. (2011) established a parallel nine channel model in rolling motion with homogeneous flow model and obtained the stability boundary in rolling motion. It was found that the unstable regions occur in both low and high equilibrium quality regions. In high equilibrium quality region, the multiplied period phenomenon was found and the chaotic phenomenon appeared on the right of marginal stability boundary. Shen et al. (2015) established a lumped model for the flow instability in parallel rectangular channels in heaving motion. Their results showed that the heaving amplitude contributed slightly to the instability. This conclusion is in agreement with the results of Tan et al. (2009) and Tang et al. (2014).

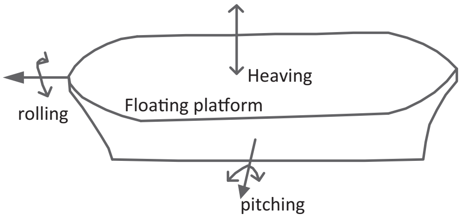

Fig. 1. Schematic of ocean motions.

The investigations for the two phase flow instability in ocean motions were mainly carried out with time domain method or experimentally (Yan, 2017). The results of time domain method could only be used to specific facilities although it could simulate nonlinear phenomenon. However, the results obtained by frequency domain method are more general. The Liapunov theorem indicated that the stability of the linearized system corresponds to the stability of the nonlinear system operating under quasi-equilibrium conditions (Porter, 1968). Therefore, the analysis with frequency domain method in quasi-equilibrium conditions was valuable. In this work, the DWO in a uniformly heated channel in ocean motions was investigated by using frequency domain method and reduced order models. The reduced order model of Mishra and Singh (2016) was introduced and the effect of ocean motions was included. The reduced order models included a minimum number of equations describing the physical phenomena of interest, while the geometrical complexity was reduced to a few-channel model (Dokhane, 2004). The objective of such models is to obtain the basic physical mechanisms involved in dynamical system beyond the stability boundary, with the nonlinear dynamics and bifurcation theory. Usually these models are formulated as systems of partial differential equations and then transferred into ordinary differential equations. The stability boundary is finally obtained by solving the Jacobian matrix.