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# Modeling of flashing-induced flow instabilities for a natural circulation driven novel modular reactor

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ABSTRACT

An analytical study based on frequency domain analysis is presented on the flashing-induced flow instability in a natural circulation test facility, which was designed to investigate the flow instability for a BWR-type novel modular reactor (NMR). To address the flashing phenomena at low pressure conditions, such as initial startup transients or accidents, the liquid enthalpy change in the P-T diagram due to reduced hydrostatic head in the riser or chimney was treated as an axially uniform heat flux. Based on the drift flux model, the system transfer function was obtained through small perturbations about the steady state in the frequency domain. The D-partition method was used to determine the neutral stability boundary in the dimensionless stability plane, which was constituted of the subcooling number and phase change number. From the frequency domain analysis, the flashing stability boundary and the density wave oscillations boundary could be predicted. Some parametric studies had been performed on the system pressure and the inlet flow resistance coefficients in the stability analysis. The results showed that the flashing stability boundary was more sensitive to the system pressure than the density wave oscillations. In addition, the theoretical stability boundaries were benchmarked against the experimental stability boundaries from quasi-steady state tests. Although the general stability boundary agreed well with the experiments, certain discrepancies still existed due to the assumptions of thermal equilibrium in current study. In the future, the thermal non-equilibrium conditions including subcooled boiling will be taken into account in the flashing induced stability analysis.

## 1. Introduction

The flashing induced stability problem, simplified as flashing instability, in two-phase flow system is of great importance to the safe operation of naturally driven nuclear reactors and passively safe engineering safety system in nuclear industry. The designs of naturally driven nuclear reactors, ranging from conventional nuclear reactors to small modular reactors (Shi et al., 2016), feature a relative long chimney section above the reactor core to increase the driving force of natural circulation. In addition, the design of the reactor cavity cooling system for the generation IV reactors characterizes a long riser above the cooling panel (Lisowski et al., 2011). The flashing instability could easily occur in the chimney section due to reduced hydrostatic head during the initial startup transients of the nuclear reactors, or in the riser section for the reactor cavity cooling system during accidental scenarios. The void fraction increases in the chimney section due to the flashing evaporation. The flow fluctuations caused by the flashing instability usually have large magnitude depending on the system design. Therefore, the safe operation or the system performance would be largely affected by the flashing instability. Although the flashing instability have been widely investigated experimentally and numerically in the last decade (Inada et al., 2000; Furuya et al., 2005; Manera et al., 2005; Hu and Kazimi, 2011; Lee et al., 2015; Su et al., 2002; Guo et al., 2016), the difficulties of predicting the flashing instability still exists due to its complexity. The demand to improve and develop the mechanistic model for the flashing instability becomes much urgent and necessary especially with the advancement of the next generation nuclear plants (NGNP).

A recent research has been performed to investigate the flow instability in a Novel Modular Reactor (NMR) design for low power and low pressure conditions. The NMR developed at Purdue University is a BWR-type small modular reactor design, which relies on natural circulation to provide driving force for both nor-

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### Nomenclature

*Latin letters*

| | |
|---|---|
| $A$ | flow area [m$^2$] |
| $c$ | specific heat [J/kg-K] |
| $C_k$ | kinematic wave velocity [m/s] |
| $c_p$ | specific heat at constant pressure [J/kg-K] |
| $D$ | hydraulic diameter [m] |
| $f$ | friction factor or frequency [–] |
| $g$ | gravitational acceleration [m/s$^2$] |
| $i_{fg}$ | latent heat of vaporization [J/kg] |
| $j$ | volumetric flux or center-of-volume velocity [m/s] |
| $K$ | K factor (Minor loss coefficient) [–] |
| $l$ | heated section length [m] |
| $L$ | axial length scale [–] |
| $\dot{m}$ | mass flow rate [kg/s] |
| $\mathrm{N}$ | dimensionless number [– |
| $\mathrm{N_{Fr}}$ | Froude number [–] |
| $\mathrm{N_{fl}}$ | flashing number [–] |
| $\mathrm{N_{sub}}$ | subcooling number [–] |
| $\mathrm{N_{Zu}}$ | Zuber (phase change) number [–] |
| $p$ | pressure [Pa] |
| $q$ | power [w] |
| $q''$ | heat flux [w/m$^2$] |
| $q'''$ | volumetric heat generation rate [w/m$^3$] |
| $s$ | complex number [a + bi] |
| $t$ | time [s] |
| $T$ | temperature [K or °C] |
| $v$ | velocity [m/s] |
| $V$ | volume [m$^3$] |
| $V_{gj}$ | drift velocity [m/s] |
| $z$ | axial coordinate [m] |

*Greek*

| | |
|---|---|
| $\alpha$ | void fraction [–] |
| $\Gamma_g$ | mass generation for the vapor phase [kg/m$^3$-s] |
| $\Delta$ | difference [–] |
| $\varepsilon$ | infinitesimal [–] |
| $\bar{\lambda}$ | non-boiling length [m] |
| $\Lambda_n$ | various transfer function [–] |
| $\mu$ | dynamic viscosity [kg/m-s] |
| $\nu$ | kinematic viscosity [m$^2$/s] |
| $\xi$ | perimeter [m] |
| $\rho$ | density [m$^3$/s] |
| $\tau$ | time scale [–] |
| $\tau_{01,12,23,34,13}$ | residence time in Regions (A), (B), (C), (D), and in the heated section [s] |
| $\Omega$ | characteristic frequency [–] |
| $\omega$ | frequency [–] |

*Superscripts*

| | |
|---|---|
| $*$ | dimensionless |

*Subscripts*

| | |
|---|---|
| $e$ | exit/Region D |
| $f$ | liquid |
| $fl$ | flashing |
| $g$ | gas |
| $h$ | heated |
| $i, in$ | inlet |
| $k$ | each phase |
| $m$ | mixture |
| $me$ | mixture in Region D |
| $o$ | reference point/component |
| $s$ | saturation |
| $sub$ | subcooling |
| $W$ | Wall |
| $w$ | wetted |
| 3 | bottom of Region D |
| 4 | top of Region D |
| 12 | Region B |
| 23 | Region C |
| 34 | Region D |

*Operators*

| | |
|---|---|
| – | time average |
| $\frac{D_k}{D_t}$ | $= \frac{\partial}{\partial t} + v_k \cdot \nabla$ |

mal operations and accidental management (Ishii et al., 2015; Wu et al., 2016; Odeh and Yang, 2016). In previous research, a natural circulation test facility was scaled and designed from the NMR by using the three-level scaling method. The experimental study of startup transients of the NMR showed that more than one flow instability mechanisms occurred in the natural circulation test facility during the normal initial startup procedures (Shi et al., 2015a,b). From the experimental research, two startup procedures, i.e., very slow startup procedures and pressurized startup procedures, were proposed for the initial startup procedures for the NMR (Shi et al., 2014) to eliminate the flow instabilities. In addition, the experimental stability maps were obtained under low pressures by performing quasi-steady state tests (Shi et al., 2015c). Following the experimental research, the theoretical stability analysis in the frequency domain has been carried out to predict the observed flow instabilities occurred in the test facility (Shi, 2015).

In this paper, a new flashing mechanistic model related to the flashing number combining with the linear frequency domain analysis under thermal equilibrium conditions have been developed to predict the flow instability boundary for the NMR. Section 2 introduces the fundamental basis for the frequency domain analysis, including the one-dimensional drift flux model, flashing instability model, detailed derivations of the kinematics and dynamics of the fluid in the riser section. Section 3 presents the experimental stability boundaries from the quasi-steady state tests in a small-scaled natural circulation test facility. Section 4 presents the theoretical stability maps and discusses the uncertainties between the theoretical and experimental stability maps. Key conclusions are summarized in Section 5.

## 2. Frequency domain analysis

The basic method used in this research to study the flashing instability is called linear frequency domain stability analysis, which can be used to obtain stability boundaries for a flow system. This method is a conventional way to analyze other flow instabilities such as the density wave oscillations (DWO) (Shi et al., 2016) and Ledinegg instability (flow excursion) etc. The frequency domain analysis in this research was based on the drift-flux model and its constitutive equations (Zuber, 1967) for a two-phase flow system. For example, through applying a small perturbation about the steady state in the inlet flow velocity, the system transfer