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Review

Startup instability in natural circulation driven nuclear reactors

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ABSTRACT

Natural circulation driven nuclear reactors are prone to flow instability during the startup transients. This paper intends to provide the state-of-the-art reviews on the theoretical analysis and experimental studies on flow instability in three types of natural circulation driven reactors, ranging from conventional nuclear reactors to small modular reactors. Brief overviews of three categories of startup flow instability, i.e., density wave oscillations, flashing instability, and Geysering instability, are provided. A critical review is conducted for the scaling analysis and design of small scaled test facility. The review of obtaining quasi-steady state stability maps in the dimensionless stability plane through frequency domain analysis and experimental tests provides the state-of-the-art methodology of analyzing the flow instability. Experimental startup instability during different initial startup procedures is reviewed. Although extensive efforts have been made to study the flow instability, further work is required to improve the scaling ability of experimental investigation and the accuracy of code analysis. Some discussions for future research directions are given.

1. Introduction

The boiling water reactors (BWR) generate around 20% of overall nuclear electricity based on the IAEA data in 2015. The BWRs in operation are mainly designed by General Electric (GE) including generations from BWR/1 to BWR/6 in the US. Since 1980s, GE also developed advanced boiling water reactor (ABWR), simplified boiling water reactor (SBWR), and economic simplified boiling water reactor (ESBWR). Apart from the conventional BWRs, some small modular reactors (SMRs) are also in fast development by taking advantage of mature boiling water technology, such as the Mitsubishi's integrated modular water reactor (IMR) with a thermal output of 1000 MW (Hibi et al., 2004), and Purdue's novel modular reactor (NMR-50) with a thermal output of 165 MW (Ishii et al., 2015). The design of reactors mentioned above except for the BWRs/1~6 eliminate the recirculation loops and pumps by utilizing natural circulation to provide the driving force, which is induced by the density difference between the hot leg and cold leg. However, the driving force for the natural circulation is especially weak when the system pressure or power level is low. Flow instability has been widely observed and investigated during the initial startup transients or accidental scenarios for natural circulation driven water reactors. Three flow instability mechanisms, i.e., density wave oscillations (DWOs), flashing instability, condensation induced flow instability (Geysering instability), has been mostly reported and studied through both theoretical analyses and experimental tests.

This paper aims to provide deep insights of the flow instabilities especially in natural circulation driven water reactors. Section 2 describes the flow instability mechanisms. Section 3 presents the popular analysis methods. Section 4 introduces the scaling methods and analysis to build test facility to study flow instability experimentally. Section 5 presents the theoretical and experimental methods to obtain the steady state stability maps. Section 6 introduces existing research on the flow instability during the startup transients. And the key conclusions are summarized in Section 7.

2. Major flow instabilities encountered in boiling-type nuclear reactors

2.1. Density wave oscillations in normal operations

The most common dynamic flow instability in the two-phase flow system is the density wave oscillation, which is also named as thermally induced flow instability caused by kinematic-wave

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(density wave) propagation (Ishii, 1971, 1976). The mechanism of the DWOs in a single heated channel can be explained through Fig. 1. If the inlet flow is perturbed sinusoidally, the change of mixture density will be delayed due to the existence of the time-lag effects (residence time) in both single-phase and two-phase flow. Then local pressure drop fluctuates in a similar pattern but also with certain time delays due to the propagation of density waves. In certain conditions, the total pressure drop of the heated channel can be 180° out-of-phase with respect to the inlet flow velocity. As can be seen in Fig. 1, the biggest channel pressure drop can correspond to the smallest inlet flow velocity, which is considered unstable. Sustained oscillations occur if a self-exciting relation is satisfied between the inlet flow velocity and internal pressure drop. The detailed analysis of the DWOs can be found in a report (March-Leuba, 1992). The procedures to avoid DWOs have been developed based on the quasi-steady state stability maps. Various parameters affecting the boundary of the stability can be analyzed using the stability maps (Ishii, 1971). For example, adding the flow resistance (K factor) at the channel inlet is an effective method to prevent the DWOs.

2.2. *Flashing instability during the initial startup transients*

The flashing instability has been widely investigated during the normal initial startup procedures for natural circulation boiling water reactors (NCBWRs). The flashing instability occurs due to the design of a long chimney section to enhance the driving force in NCBWRs. Under low system pressures, the saturated coolant at the top of the heated section becomes superheated when it flows upward due to reduced hydrostatic head in the relatively long chimney above the core. The evaporation of the superheated coolant increases significantly the void fraction to raise the natural circulation flow rate. However, the suddenly increased flow velocity can bring in large amount of subcooled coolant into the active heated region from the downcomer causing the reduction of the driving force. Therefore, the natural circulation flow rate can experience many intermittent flow oscillations before the flashing is completely suppressed under high system pressure (Shi et al., 2015a). The flashing instability disappears when the system pressure beyond certain value, which is 0.5 MPa confirmed by many researchers. The quantification of the flashing instability can be addressed by a properly defined flashing number. In addition, the flashing instability can be avoided by using either very slow power ramp rate or pressurized startup procedures.

2.3. *Condensation induced flow instability during the initial startup transients*

The condensation induced flow instability (Aritomi et al., 1992, 1993) is also named as the Geysering instability, which is quite opposite to the flashing instability regarding to the flow instability phenomena. It usually happens in the upper plenum near the core exit. The bubbles generated in the core section can experience subcooled conditions in the upper plenum under low pressure conditions. Therefore, the bubbles collapse to increase the local temperature and change the mixture flow velocity. The Geysering instability can be observed during the startup transients, during which subcooled conditions are dominant at low pressure and low power levels. The Geysering instability disappears once saturated conditions are developed with increased system pressure. Therefore, similar to the flashing instability, the Geysering instability can be avoided by using the pressurized startup procedures.

3. Analysis method

For the BWR stability analysis, there are generally two widely used analytical approaches to investigate the flow instability: frequency domain analysis and time domain analysis. The neutronics models are usually coupled with thermal-hydraulic models to study the flow instability in both methods.

3.1. *Frequency domain analysis*

Most of the field equations describing the system dynamics are complicated non-linear partial differential equations. These non-linear equations can be turned into linear conservative equations in the frequency domain. Therefore, it is also called linear frequency domain stability analysis. The system governing equations are linearized by small perturbation about steady-state, and transfer functions can be obtained between perturbed variables. Due to simplifications of the linearization, the frequency domain analysis can be used to obtain the stability boundary, i.e., the onset of flow instability, for the density wave oscillations based on certain stability criterion. The frequency domain analysis codes include FABLE/BYPSS, HIBLE, LAPUR-5, NUFREQ (D'Auria et al., 2005; Su et al., 2002) etc. The general approach of the frequency domain analysis of the density wave oscillations is introduced as follows.

The system of interest consists of four components, i.e., upstream single-phase unheated section, single-phase heated section,

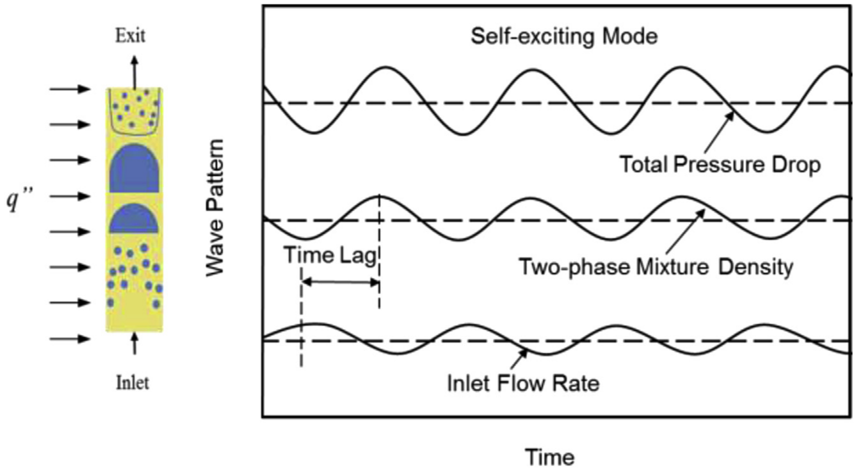

Fig. 1. Density wave oscillations.