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Research of two-phase flow instability in parallel narrow multi-channel system

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ABSTRACT

Two-phase flow instabilities have been highly researched in the past decades. Many researches gave different stability criterions based on experiments or calculations. However, most of the experiments were designed for studying the specific type of instability, but sometimes what we want to know is the stabilities of one specific system. In this paper, a comprehensive study of two-phase flow instabilities in parallel narrow multi-channel system was done by RELAP5/Mod3.4 code. Firstly, a direct comparison was made of the stability boundaries obtained by experimental data and RELAP5/Mod3.4 code to verify the accuracy of RELAP5 code. Good agreement between the experimental and code prediction results was achieved. Then, the two-phase flow instabilities of parallel narrow multi-channel system were investigated in sequence. The in-phase and out-of-phase parallel channel instabilities (PCI), the Ledinegg instability and the out-of-phase density wave instability (DWI) induced by Ledinegg instability in parallel narrow multi-channel system had been investigated respectively. The effects of system parameters on the stability characteristics were also explored. It is found that the instability analysis of parallel narrow multi-channel system should include the above mentioned four types, which can constitute a complete picture of a system's instability.

1. Introduction

In CHINA more and more cities become the night bright as daytime with consuming more energy. And the carbon emission is the key, which will influence the economic growth profoundly. Although Fukushima accident will have some serious influences on the development plan, the nuclear power is still one choice of Chinese government. Obviously, the nuclear power system safety will be paid more attention. The thermal–hydraulic stability is important for the design, operation and safety analysis of many industrial systems and equipments where the two-phase flow is involved, such as once through steam generator, the reactor core and reboiler. The two-phase flow instabilities have very adverse influences on thermal–hydraulic system, oscillations of mass flow rate and system pressure may generate severe structural vibration, transient burn-out of the heat transfer surface and degrade the heat transfer performance. Hence, the job of predicting the thresholds of flow instabilities in order to avoid unwanted instabilities is very necessary.

Two-phase flow instability was introduced in the literature by Ledinegg (1938). Boure et al. (1973) classified instabilities in boiling systems into static and dynamic instabilities. Many researches gave more extensive classifications. One of the most important static instabilities is Ledinegg instability. This type of instability occurs at that the slope of the channel pressure drop versus flow rate curve is negative, and the mass flow rate changes to a lower value suddenly. The subsequent researchers (Sulfredge, 1997; Hamidouche and Bousbia-salah, 2006; Hamidouche et al., 2009; Zhang et al., 2009a; Sadik and Cao, 2009) did many studies on Ledinegg instability. Some authors considered the onset of significant void (OSV) generation in the heated channel as sufficient condition to estimate the onset of Ledinegg instability (Gopinath and Vijay, 1999; Babelli and Ishii, 2001). DWI is the most common type of dynamic instabilities in heating channel system. Fukuda (1979a) classified the density wave oscillation into two types: Type-I and Type-II. Usually, the Type-I DWI will occur in the regime of the nearly zero equilibrium quality region, and Type-II DWI will occur in the regime of high equilibrium quality at outlet of tube. The DWI has been studied widely and carefully (Boure et al., 1973; Su, 1997; Su et al., 2002). In recent years, a great deal of attention has been paid to the study of dynamic PCI. The flow instability in a multi-channel system is different from that in a single-channel system due to very complicate channel-to-channel interaction. During such an instability event, the mass flow rate and the steam generation rate among parallel channels may oscillate out-of-phase with a large magnitude while a constant total mass flow rate is kept. Many investigators focused on the generating condition of stability criterion of PCI (Fukuda, 1979a,b; Lee and Pan, 1999, 2005; Guo et al., 2008a,b, 2010; Zhang et al., 2009b). Recently, some authors attempted to apply

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the thermal–hydraulic system analysis code RELAP5 to do the instability analysis (Urbonas et al., 2003; Hamidouche and Bousbia-salah, 2006; Hamidouche et al., 2009; Durga Prasad et al., 2008; Costa et al., 2008a,b).

Previous researches were mainly concerned with some particular test sections to study one of the instabilities. And those experimental data had limitations because of the experimental condition and specific test equipment. This is not enough to obtain the whole stabilities of a particular system. In present study, the parallel narrow multi-channel system will be simulated by RELAP5/MOD3.4 code and the working fluid is water. The RELAP5/MOD3.4 code has been used in several narrow channel transient analyses (Liu et al., 2006; Lu et al., 2009, 2011). Hence it was chosen as analysis tool. The two-phase flow instabilities will be studied carefully with the influences of various parameters. The classic instability phenomena existed in single channel system, such as flow excursion, in-phase DWI will also be studied in a typical parallel narrow multi-channel system. The first part is about the experiment of two-phase flow instability in vertical parallel channels. The calculation results of RELAP5/MOD3.4 will be compared with the experimental data. The second part discusses the out-of-phase DWI encountered in the parallel narrow multi-channel system; the influences of main operating parameters on the system behavior will be presented. The flow excursion (Ledinegg) instability is analyzed in Section 3. The origination conditions and influences of some parameters on Ledinegg instability are discussed detailed in this part. At last Section 4 discusses the in-phase DWI and the possible mechanism is investigated.

2. Verification of the RELAP5 model

RELAP5 is a light water reactor (LWR) transient analysis code. It was developed for best estimate transient simulation in water-cooled reactor system. The two-fluid formulation is good for the study of two-phase flow instability (Nuclear Safety Analysis Division, 2001a,b).

2.1. Description of nodalization

In this part, the experiment of two-phase flow instability in vertical parallel channel system is simulated by the RELAP5/MOD3.4 code (Guo et al., 2010; Huang, 2005). A RELAP5 nodalization for the test section is performed as shown in Fig. 1. The detailed geometry parameters can be found in Guo et al. (2010). Specified boundary conditions are considered in order to study the effects of different parameters. The inlet water temperature is fixed using a time dependent volume (010TDV), so the fluid flows into the heated channel with a constant inlet subcooling. The outlet pressure boundary condition is set by time dependent volume (020TDV). The parallel channels are connected by one branch component (014B) at the lower plenum and another branch component (016B) at the upper plenum. The inlet mass flow rate is specified using a time dependent junction (011TDJ). The heated channels are simulated by two pipes (110P and 210P). The heating power is assumed to be equality in axial direction and fixed to each node of the pipe. The inlet throttle is given as energy loss coefficient of single junction (101J or 201J).

2.2. Qualification of nodalization

Many researchers think that a qualified code may predict unrealistic results when the nodalization is not properly qualified (D'Auria and Galassi, 1998; Ambrosini, 2008), so before applying RELAP5 code to study the instabilities of parallel multi-channel system, the number of nodes in each heated channel (110P and 210P) is assessed by a comparison of instability powers at onset of instability obtained by RELAP5 at different operating parameters (Table 1). The powers at onset of instability under different node numbers are shown in Fig. 2. There are three curves for three operating cases at several different node numbers, and they have similar trend. In small node number region the results are very sensitive to the node number of the heated channel. With the increase of node number, the power at onset of instability of out-of-phase DWI became

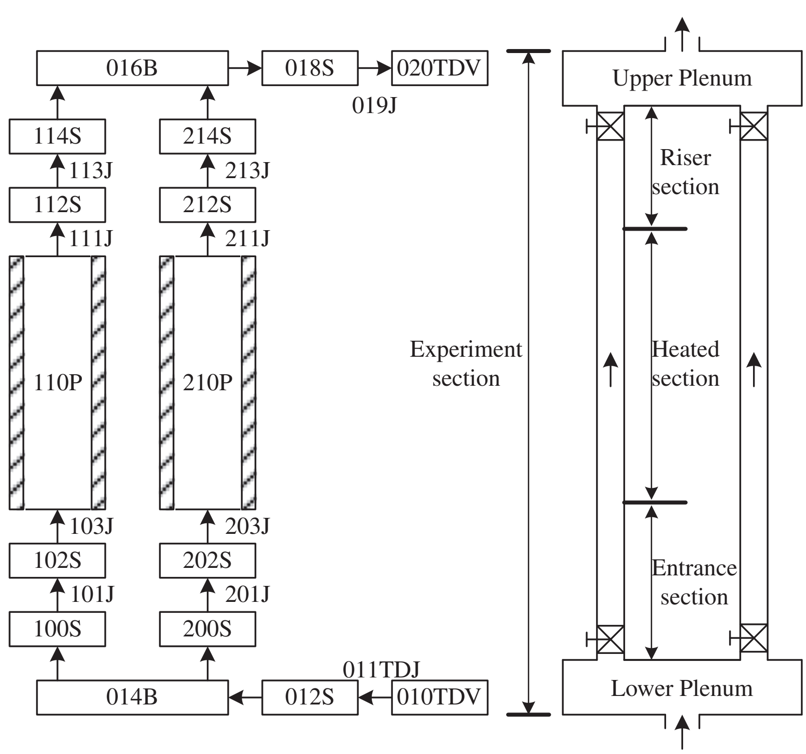

Fig. 1. Schematic of the multi-channel system and RELAP5 nodalization.