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Review

Review of research on flow instabilities in natural circulation boiling systems

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Abstract

Safety concerns of nuclear reactors have attracted the attention of researchers on flow instabilities in natural circulation boiling loops. This paper presents the state of the art in this area by reviewing a number of contributions. A large number of experimental and numerical investigations have been conducted to study and understand the conditions for inception of flow instabilities, parametric effects on instabilities, and the system behaviour under such conditions. Work done on instabilities due to channel thermal hydraulics as well as neutronics thermal hydraulics coupling has been reviewed. Different methods of analysis used by researchers and results obtained by them have been discussed. Various mathematical models and numerical techniques adopted for developing computer codes have also been discussed. The findings reported in the investigations made in the past three decades have been summarized to present the state of the art of the understanding of flow instabilities in natural circulation boiling systems.

Keywords: Natural circulation; Two-phase flow; Boiling water reactor; Boiling channels; Flow instabilities; Thermal hydraulics

1. Introduction

Steam generation systems are subjected to flow instabilities due to parametric fluctuations, inlet conditions, etc., which may result in mechanical vibrations of components and system control problems. Analysis of these instabilities in natural circulation boiling loops is very important for the safety of nuclear reactors and other boiling systems. Instabilities in boiling channels occur due to external and internal disturbances. External disturbances (perturbation transients) include fluctuations in mass flow rates (due to recirculation pump trip), sudden increase in steam flow (increase in demand), fluctuations in inlet enthalpy, fluctuations in heat supply rate, etc. Internal disturbances include flow pattern transition due to heat transfer to the fluid. These instabilities generally prevail during start-up/shutdown transients, triggering large parametric fluctuations that may lead to accidents. Thus, the study of dynamic behaviour of the system is essential to develop efficient control systems for safe operation.

Flow in boiling channels is driven by external source (forced circulation) or by buoyancy force due to density difference of two phases (natural circulation). Earlier, all boiling water reactors (BWRs) were operated with forced circulation only. However, natural circulation is an important mode of operation for removing shutdown decay

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heat during accidents in such reactors. The latest generations' BWRs are designed with natural circulation as the operation mode under both normal and abnormal conditions. The economic simplified boiling water reactor (ESBWR) designed by GE (Hinds and Maslak, 2006) and the advanced heavy water reactor (AHWR) being developed in India (Sinha and Kakodkar, 2006) are natural circulation BWRs (NCBWRs). In NCBWRs, the heat removal from the core takes place by natural circulation during the rated full power operating condition as well as the start-up and accidental conditions. Use of natural circulation is very common in fossil-fuel boilers also.

The present article reviews the work done on instabilities in natural circulation boiling loops. It is a revised, expanded and updated version of a paper presented in a conference (Durga Prasad et al., 2005) by the authors. Section 2 discusses classification of instabilities and explains various types of instabilities. Various approaches to mathematical modelling of natural circulation boiling systems and different numerical codes are discussed in Section 3. Section 4 reviews the investigations on nonlinear dynamics of natural circulation boiling systems. Experimental investigations are discussed in Section 5. The paper ends with concluding remarks in Section 6.

2. Flow instabilities

A boiling channel with subcooled inlet conditions, and heated along its length, will have two basic flow regions: one is the single-phase region, which extends from channel inlet to boiling boundary (the point at which boiling starts), and the other is two-phase flow region in which the vapour and liquid coexist. The two-phase mixture plays an important role in heat transfer process and pressure drop in boiling channels. A close coupling exists between hydrodynamic and heat transfer processes in two-phase flow systems. The addition and removal of heat from a two-phase flow cause variations in the amount and distribution of each phase and the flow pattern or topology of the flow. These changes, in turn, induce variations in local heat transfer processes. Because of the continuous change of all the thermal and hydraulic properties of the flow, the situation at any axial point in the channel can never be fully developed either thermally or hydrodynamically. As the flow is not in equilibrium, the flow properties fluctuate both upstream and downstream of the point considered (Collier, 1994). The parameters such as void fraction distribution, flow pattern and its transition, temperature distribution and heat transfer coefficient along the boiling channel play an important role in the system stability. The knowledge of their behaviour under different operating conditions is important for design and safe operation of boiling systems, particularly nuclear reactors.

Natural circulation: Flow under natural circulation is inherently less stable and experiences flow instabilities compared to the forced circulation mode, due to relatively small hydraulic driving head. In natural circulation loop, the heating process in the heater section is the driving force for the flow. The heat supplied will generate buoyancy and the flow will be created in the loop such that, in steady state, the buoyancy is balanced by friction. If the heating power is increased further, the flow rate will also increase. On further increasing the heating power, the flow velocity may be so large that sufficient time is not available for the fluid to be heated, and subcooled fluid enters the riser section and the buoyancy force reduces. The flow gets decelerated and even reversed. Therefore, a self-sustained oscillation is created which may be chaotic if the inlet subcooling is sufficiently large at a given heating power. These thermal hydraulic oscillations in the two-phase natural circulation loop are quite similar to Lorentzian water wheel (Wu et al., 1996).

Flow instabilities are of different types depending on the system configuration and operating conditions. One of the early works on flow oscillations was by Jain et al. (1966), whose experimental investigation provided detailed information on the onset of oscillatory behaviour and the effect of riser and test section dimensions. On the basis of primary features such as oscillation periods, amplitudes, and relationships between pressure drop and flow rate, flow instabilities have been classified into several types, which were first proposed by Boure et al. (1973). BWRs are generally susceptible to three types of instabilities, as classified by March-Leuba and Rey (1993).

1. *Control system instabilities*: These are due to the malfunction of reactor hardware. Suitable control mechanisms are provided to deal with this type of instability.
2. *Thermal hydraulic instabilities*: These are caused by self-oscillation of two-phase flow heated channel due to density wave effects. These instabilities are primarily classified as static and dynamic. These instabilities are discussed in Sections 2.1 and 2.2. Some static and dynamic type instabilities occur particularly during start-up conditions. These instabilities are discussed in Section 2.4.