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Study of startup transients and power ramping of natural circulation boiling systems

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ABSTRACT

Numerical models of a natural circulation test facility and its prototype have been developed with RELAP5/MOD3.4 code and verified for their grid independence by nodal sensitivity studies. The model of the test facility has been validated for its steady state as well as transient predictions with the help of experimental observations. The transient predictions and parametric trends obtained by the numerical model of the prototype have been compared with those of the numerical model of the test facility. Thus, the ability of RELAP5 code to predict the transients during startup of a natural circulation boiling water reactor is verified. A powering procedure for the test facility has been conceptualized with the help of its RELAP5 model and demonstrated experimentally. Based on this, a similar powering procedure for the prototype has been proposed and simulated numerically with its RELAP5 model.

1. Introduction

In the recent past the use of natural circulation in boiling water reactors (NCBWRs) has been highly recognized for its inherent passive safety feature and the potential for improved economy in nuclear power generation. However, the use of natural circulation has generated concern regarding operating conditions, especially related to the startup phase of the reactor. For safe operation of a natural circulation boiling water reactor, it is important to devise an appropriate startup procedure during which the system has to pass from single-phase to two-phase operation. At low pressures, a natural circulation loop typically has three operation ranges: a single-phase stable region, a two-phase unstable region and a two-phase stable region. Thermal-hydraulic instabilities for natural circulation boiling loops have been classified into two major categories: Type-I and Type-II (Fukuda and Kobori, 1979). An NCBWR is susceptible to Type-I instabilities when it starts from low pressure and low temperature conditions. These instabilities are often induced by the phenomena of geysering in the heated channel and flashing in the riser section. Under certain conditions, geysering instabilities can occur in a two-phase natural circulation loop at low pressure and low power. Fundamental studies in the area of geysering instability have been conducted by Aritomi et al. (1992) and Wu et al. (1996). A detailed study on flashing-induced instability and its difference from other type of instabilities has been done by Furuya et al. (2005) in their experiment conducted on SIRIUS-N facility. The phenomenon of geysering-induced flashing instability was reported by Jiang et al. (2000). During geysering, a gradual increase in riser fluid temperature is observed which makes the water to flash at the exit of the riser as it reaches its saturation temperature. As a result of flashing, the system flow rate increases which leads to a subcooled condition in the core and at the inlet of the riser. Thus, a condition for the occurrence of geysering is created.

A normal startup procedure for an NCBWR design has been discussed by Kuran et al. (2006). The startup procedure is divided into four distinct phases: Phase I – single-phase core heat up, Phase II – net vapor generation in core, Phase III – saturated chimney, and Phase IV – power ascension to full power. The nature of transition through Phase II and Phase III is important, where the instabilities like geysering (in Phase II) and flashing (in Phase III) are highly dominant. From literature, it appears that a consensus has been reached that the above mentioned Type-I instabilities can be suppressed or avoided by having an increased system pressure around 15–20 bar (Chiang et al., 1994; Manera and van der Hagen, 2003; Subki et al., 2003). A brief survey on the various startup procedures proposed by various authors conveys that different methodologies can be adopted in raising the system pressure to the desired level (Manera, 2003). For example, one of the procedures is to externally pressurize the system by injecting nitrogen or steam. Once the pressure in the vessel is high enough, the reactor power can be increased to achieve two-phase natural circulation. Unfortunately this procedure needs an external boiler of adequate volume and power and the related connecting piping to the reactor vessel. Manera (2003, 2005) proposed a procedure for creating a steam cushion in the

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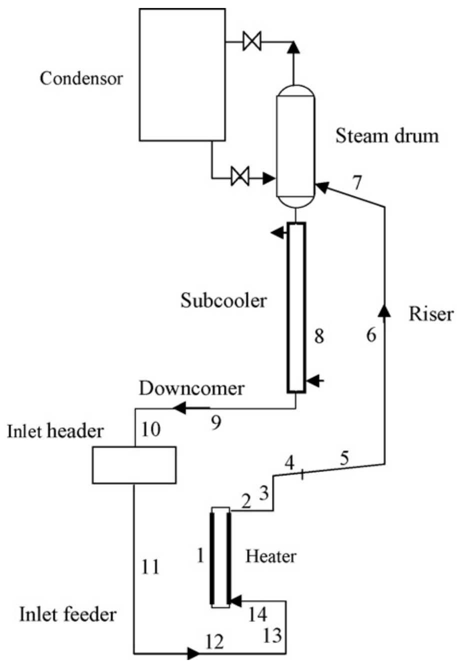

Link No.	Inner Diameter (mm)	Length (mm)	Change in elevation (mm)
1	32.50	1200	1200
2	18.90	200	0.0
3	18.90	430	430
4	18.90	530	66
5	32.50	4115	514
6	32.50	5890	5890
7	32.50	1010	160
8	15.58	6614	-6614
9	15.58	1640	0.0
10	15.58	200	-200
11	24.30	2040	-2040
12	24.30	1615	0.0
13	24.30	990	990
14	24.30	310	0.0

Fig. 1. Schematic view of Natural Circulation Test Facility (NCTF) loop.

system without using steam pressurized in external vessels. This is done by allowing flashing to occur at the top of the riser by making the reactor critical at low pressure. During startup, as the system pressure crosses the Type-I region and enters the stable region (Phase IV), the power is further increased so as to take the system to the normal operating pressure. Here, the power applied at every instant should be such that the system is well below the Type-II boundary (at the instantaneous pressure) throughout the process. A power ramping procedure based on this concept, which aims at a safe and faster pressurization of the system was devised with the help of RELAP5 and demonstrated on a test facility (Lakshmanan et al., 2008). The present work deals with the scalability of this powering procedure to the prototype NCBWR.

A number of boiling channel natural circulation test facilities have been constructed to study thermal hydraulic instabilities that could occur in a BWR. The Natural Circulation Test Facility (NCTF) (Iyer and Kadengal, 2003) is a scaled model designed to investigate various phenomena involved right from startup to operating condition of a pressure tube type NCBWR (Sinha and Kakodkar, 2006). Purdue University Multi-Dimensional Test Assembly (PUMA) is a low-pressure facility that can simulate the transients at a pressure below 1.03 MPa (Ishii et al., 1996). It is a scaled facility for the proposed simplified boiling water reactor (SBWR) design by GE. The PANDA large-scale facility (Auban et al., 2004) under the NACUSP project (Kruijf et al., 2003) is also aimed at investigating system behavior at varied operating conditions with a special interest in the phenomenon involved during startup of the reactor. Thus, a part of the research in these facilities is directed towards getting an insight into the transients at low pressure and low power conditions in natural circulation boiling systems. A review article by Durga Prasad et al. (2007), lists the experimental test facilities exiting around the world that involve study of flow instabilities under natural circulation condition.

For numerical simulation of two phase flow instabilities, a 6-equation model can be used, where the two phases are treated as two separated fluids for which mass, momentum and energy balances are solved separately. This type of model is implemented in some of the system codes (RELAP5, ATHLET, TRAC, MONA) and allows considering thermal non-equilibrium and slip between the phases. RELAP5 has been used for simulating transients in natural circulation boiling systems (Durga Prasad et al., 2008). However, the use of such codes to simulate the transients during startup conditions is yet to be fully established. Tiselj and Cerne (2000) showed that RELAP5 code cannot deal with flashing, since the results become strongly dependent on the integration time step used for the simulations. Although there are limitations in the use of RELAP5 code at low pressure, recent studies towards enhancing the predictive performance of the code under low-pressure subcooled conditions indicate promising results (Koncar and Mavko, 2003). Refinement has been done to the subcooled boiling models of the code for low-pressure conditions (Sridhar and Hassan, 2002; Tu and Yeoh, 2002; Yeoh and Tu, 2002; Dilla et al., 2006). Numerical simulations of startup transients in a natural circulation test facility using RELAP5/MOD3.4 (Lakshmanan and Pandey, 2007) showed trends similar to those observed in experiments. A list of other thermal hydraulic and neutronic codes that can be used in modeling and studying a two-phase system was given by Durga Prasad et al. (2007).

The current paper deals with two issues: one, development of numerical models with RELAP5/MOD3.4 code and its ability to predict transients occurring at low-pressure, low-power conditions; and the other, devising a power ramping procedure aimed at safe and fast pressurization of the system. RELAP5 models for the natural circulation loops of NCTF and NCBWR are developed and their predictions are verified with experimental data (Section 3). The RELAP5 model of NCTF is used to devise and implement a power ramping procedure for the test facility. Based on this, a similar power ramping procedure for NCBWR is proposed and numerically demonstrated (Section 5).

2. Natural circulation loop

The natural circulation loop studied here is a part of Natural Circulation Test Facility (NCTF) (Iyer and Kadengal, 2003). The test facility is a scaled model designed to simulate a pressure tube type reactor which is driven by natural circulation. The NCTF consists of two loops with four risers connected to two drums. While one simulator with its riser, drum, downcomer and feeder represents