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Experimental study on accident transients and flow instabilities in a PWR-type small modular reactor

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ABSTRACT

Experimental study on natural circulation flow instabilities is of great importance for the safety analysis in a PWR-type SMR, especially for accident scenarios such as loss of coolant accident (LOCA) and loss of heat sink accident (LOHS). In this study, an experimental natural circulation facility was built by scaling down from a typical PWR-type SMR. The scaling ratios were derived from non-dimensional field and constitutive equations of the drift flux model. The test facility has a height of 3.44 m with an operating pressure limit of 1.0 MPa. Two kinds of tests, the blowdown test and cold-blowdown test were performed. The blowdown test was designed to simulate the low pressure phase (< 1 MPa) of a LOCA event and evaluate the performance of the emergency core cooling system (ECCS). The test results indicate that the ECCS can keep the RPV water level above the core, and the RPV pressure keeps decreasing during the entire accident transients. The cold-blowdown test was designed to simulate the whole transients of the system blowdown at low pressure conditions. The oscillations of the pressure drop, natural circulation rate, void fraction and inlet temperature were observed and analyzed. The cold-blowdown test results were compared with the RELAP5 simulation. Although some discrepancies existed at the initial blowdown phase, the code calculation agreed well with the experiment data.

1. Introduction

Recently, Small Modular Reactors (SMR) have received considerable worldwide attention. As one kind of advanced reactors, SMRs provide enhanced safety and convenient construction/operation compared to conventional nuclear reactors. The enhanced safety mostly benefits from the employment of passive safety systems, which are usually driven by natural circulation flow. Besides, in some SMR designs, such as Mitsubishi's Integral Modular Reactor (IMR) (Hibi et al., 2004), the Purdue University's Novel Modular Reactor (NMR) (Ishii et al., 2015; Wu et al., 2015, 2016), and the NuScale Power Reactor (Reyes, 2012), etc., natural circulation driven flow is utilized to transfer the fission energy, which can eliminate the primary loop circulating pump and greatly simplify the reactor design. It is obvious that the fundamental understanding of natural circulation instability is critical to the design and safety of SMRs.

The stability of a system is defined as the ability of a system returning to the original steady state after a small perturbation. The flow instabilities are usually characterized by sustained oscillations of flow rate, system pressure or other flow parameters. Compared to forced circulation systems, natural circulation systems are more unstable especially at low power and low pressure conditions because of the low driving force and more nonlinearity of natural circulation process. The instability is particularly significant when boiling is involved and the flow becomes two-phase natural circulation. Numerous experimental investigations in two-phase natural circulation loops have been conducted (Saha et al., 1976; Guanghui et al., 2002; Jiang et al., 1995; Qiu et al., 2003; Kyung and Lee, 1994). However, only few of these experimental facilities are specifically scaled down from SMRs. Most of these experimental natural circulation loops are designed to conduct parametric studies or focus on mechanisms of several specific phenomena. The scaling distortion could be significant hence the data collected in these facilities may not characterize the two-phase flow in a small modular reactor.

Furuya et al. (Furuya et al., 2005) experimentally studied the flushing-induced density wave oscillations in a natural circulation BWR, and Manera et al. (Manera et al., 2005) modeled these instabilities using two-phase flow code FLOCAL. Shi et al. (Shi et al., 2015a, 2015b, 2015c, 2016; Shi and Ishii, 2017) experimentally investigated the natural circulation flow instability for a BWR-type SMR,

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namely NMR-50 (Ishii et al., 2015). Flashing instability as well as density wave oscillation were also observed (Shi et al., 2015b), (Shi et al., 2015c). For a PWR-type SMR, although the main flow remains single-phase in normal operation conditions, two-phase flow could exist under certain accidental scenarios such as loss of coolant accident (LOCA) and loss of heat sink accident (LOHS). In addition, the two-phase natural circulation flow is essential to the emergency core cooling system (ECCS) for the decay heat removal in reactors with passive safety system designs. Therefore, failure to predict the potential two-phase flow instabilities under these conditions could affect the accident management. However, most previous researches (Modro et al., 2003) (Reyes and Young, 2011), related to PWR-type SMRs focus on the verification and validation of the concept and the function of the passive safety system, and few of them concentrate on the potential stability issues of two-phase flow natural circulation.

The objective of this study is to experimentally study the accident transients as well as the thermal hydraulic flow instabilities that could occur in a PWR-type SMR during accident transients. Two kinds of blowdown tests are designed and performed and the performance of the ECCS was assessed. RELAP5 code simulation were conducted to verify scalability of the integral tests.

2. Scaling analysis

2.1. Prototype description

The NuScale reactor, a typical PWR-type SMR, was selected as the prototype of the experimental facility. Note that the design parameters of the NuScale reactor are not available in public literature. Therefore, in this study, the facility is designed and scaled based on the design parameters of the Multi-application small light water reactor (MASLWR) (Modro et al., 2003), which is the prototype of the NuScale reactor. As schematically shown in Fig. 1, the primary loop is integrated inside a reactor pressure vessel (RPV) and circulation pumps are eliminated in the primary loop. Single-phase natural circulation flow is used to drive the coolant, thus compared to BWR-type SMRs (Ishii et al., 2015), the PWR-type SMRs normally have a taller hot leg due to relative small density difference. The helical coil steam generator is located within the upper part of the RPV and outside of the hot leg riser. The RPV is contained by a steel containment, which is submerged in a large reactor pool. The containment can serve as a radiation barrier during accident scenarios. The water in the reactor pool is the heat sink of the decay heat in accidents. Two vent valves are located at the top of the RPV to avoid overpressure. In addition, two recirculation valves are located at the lower part of the RPV but above the core section to provide a flow path for the coolant from containment to flow back to the RPV. In normal operation conditions, the space between RPV and containment is in a vacuum for insulation.

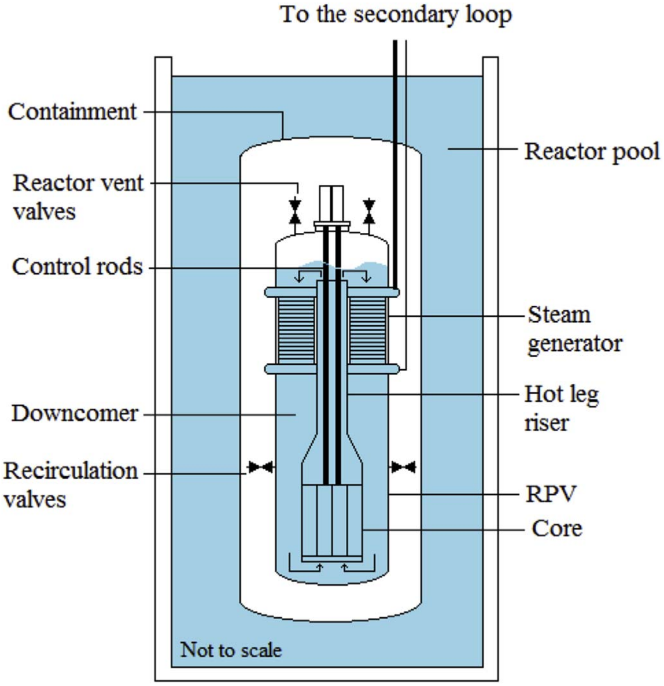

Fig. 1. Schematic of a NuScale module installed underwater (Reyes, 2012).

2.2. Test facility scaling

Ishii and Kataoka (1984) derived scaling laws for thermal-hydraulics system under single-phase and two-phase natural circulation flows. For single-phase flow, the similarity laws were obtained from the one-dimensional continuity, momentum and energy equations. For two-phase flow, a perturbation analysis based on the one-dimensional drift-flux model was used to get the similarity groups. The important similarity groups for single-phase and two-phase natural circulation are summarized in Table 1. To guarantee the similarity of simulated key phenomena, these non-dimensional number of the prototype and the test facility should be kept the same between the model and prototype. Given that the two-phase flow during accident conditions is the focus of the study, two-phase scaling criteria is applied first. Besides, the scaling criteria of two-phase flow are more restrictive than those of single phase flow, hence satisfying two-phase scaling criteria guarantees the scaling of single-phase flow. The fluids used in model and the pressure/temperature scale are the same with that in the prototype, therefore all the fluid properties are identical between the model and the prototype. By defining the general scaling ratio $(\psi)_R$ as

$$(\psi)_R = \frac{\psi_m}{\psi_p} = \frac{\psi \ \ in \ \ model}{\psi \ \ in \ \ prototype} \tag{1}$$

The scaling criteria can be expressed as

$$(N_{pch})_R = (N_{sub})_R = (N_{Fr})_R = (N_{th})_R = (N_d)_R = 1 \tag{2}$$

The similarity requirements can be obtained by solving Eq. (2). The design of the facility can be divided into two steps: the first step is the design of the ideally scaled facility (ISF) based on the space availability without considering engineering limitations such as the availability of specific pipe size; the second step is designing the engineering scaled facility (ESF) by considering the cost and the practical limitations. By applying similarity requirements and considering the space limitations, the ISF scaling ratios are decided and given in Table 2.

Apart from the similarity requirements obtained from the field equations, some important local phenomena such as chocking, flashing and condensation should be considered separately to refine the local geometry. For example, the scaling of ADS line cross sectional area is different from the general area ratio (1/100). The model-to-prototype ratio of velocity multiplied by the cross-sectional area should be 1/200 to satisfy the conditions for the similarity of the mass and energy inventories. For the chocking flow case, the velocity ratio in the ADS line is 1/1 instead of the regular velocity ratio (1/2) due to critical flow, because the pressures and the thermodynamic conditions between the model and the prototype are the same. Therefore, the ADS line cross section area ratio is 1/200, which is different from the loop sections scaling (1/100).

The scaling analysis can be verified with RELAP5 code simulation. Fig. 2 shows RELAP5 simulations on steady state pressure and flow rate of the ISF and the prototype. The agreements of the steady state parameters indicate that the steady state operation conditions of the prototype can be well represented in the ISF. To check the similarity of the transients between the ISF and the prototype, the blowdown event is simulated in ISF and MASLWR, as shown in Fig. 3. The pressure