

Assessment of RELAP5/MOD3.2 for startup transients in a natural circulation test facility



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ABSTRACT

System level analysis codes have been proved effective tools for accident analysis and other transient analysis in nuclear reactors. With increasing interests in the natural circulation flow driven systems, flow instabilities occurring under low power and low pressure conditions have been receiving more research attention. This work aims to demonstrate the performance of one of the most widely used system codes, i.e., RELAP5, in simulating startup transients, as well as its capability to predict flow instabilities. The experimental database was acquired from a well-scaled natural circulation test facility, which was designed to investigate the startup flow instabilities for a BWR-type Novel Modular Reactor (NMR-50). The startup simulations by RELAP5/MOD3.2 code were compared with various thermal-hydraulics measurements including system pressure, temperature, natural circulation flow rate, and void fraction, etc. In addition, two power ramp rates were applied in the startup simulations to study heating rate effects on flow instabilities. In general, the RELAP5 code can consistently simulate the two startup transients and predict two flow instabilities, i.e., flashing instability and density wave oscillations, occurred in the natural circulation test facility at low pressures. The predicted natural circulation flow velocities had a good agreement with the measurements. However, the RELAP5 could underpredict void fractions in the heated section when the system is under thermal non-equilibrium conditions at low power and low pressure.

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1. Introduction

Due to the impractical cost of performing full-scale experiments, system level analysis codes, such as RELAP5, TRAC, and TRACE, have been developed for predicting system behavior under both normal and accident conditions for light water reactors (LWRs). The capabilities of these system codes, based on field equations and closure relations, have been benchmarked by a lot of data from both Integral Effect Tests (IETs) and Separate Effect Tests (SETs) in the last two decades. Most phenomena can be predicted with relative good timing and accuracy. Therefore, the system codes are widely used for the reactor design, licensing, operation, and severe accident simulation in the current fleet of commercial LWRs, which mainly use forced circulation flow driven system. With the development of advanced nuclear reactors and small modular reactors, passive system designs utilizing natural circulation flow have been widely adopted for both normal operation and decay heat removal during design basis accidents (DBAs), and even beyond design basis accidents (BDBAs). Natural circula-

tion flow mainly relies on the density difference between channels, i.e., the hot leg and cold leg, to provide system driving force. Normally, natural circulation flow rate is smaller than the flow rate in the forced circulation system. It is commonly recognized flow instabilities could occur at low pressure and low power conditions including the startup transients and certain accident conditions (Jiang et al., 1995; Su et al., 2002; Furuya et al., 2005; Manera and van Der Hagen, 2003; Shi et al., 2015a, 2015b). Of course, system analysis codes will be implemented in the analysis of the natural circulation flow driven systems. In view of the differences between the natural circulation and forced circulation systems, some existing models or closure relations in these system level analysis codes need additional verification and validation (V&V) data from both IETs and SETs for the phenomena relevant to natural circulation flow. These phenomena include flow regime transition, subcooled boiling, choking flow, and natural circulation flow instabilities at low power and low pressure conditions etc. (Shi et al., 2017b).

Previous efforts on the validation of system analysis codes (Schafer and Manera, 2006; Kozmenkov et al., 2012) using natural circulation flow data have been focused on natural circulation flow instabilities in two-phase flows, especially on flashing induced

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flow instabilities due to the reduced hydrostatic head in the chimney or riser section. There are no best codes for the prediction of flow instabilities developed to date either in the frequency domain or in the time domain (Shi et al., 2016). Due to the complexity of the flow instabilities, relative large uncertainties exist in code simulations caused by selected constitutive models and numerical schemes. RELAP5 code has been recognized as one of the best-estimate system analysis codes and selected for the simulation of the natural circulation flow driven systems by many researchers. As Bertodano et al. indicated, RELAP5 is capable to model global instabilities, in particular density wave oscillations (Bertodano et al., 2017). For example, RELAP5 code was benchmarked with low pressure data (0.1 MPa) from the CIRCUS test facility on the flashing-induced flow instabilities (Kozmenkov et al., 2012). The authors built the RELAP5 model by detailed modeling of all components of the CIRCUS facility. Good agreement was reached on the flow oscillation frequency and flow rates between simulations and measurements. Following this activity, RELAP5 code was validated against natural circulation two-phase flow instability data at 0.1 MPa pressure in CIRCUS-IV single channel tests by Phung et al. (2015). The authors developed a procedure for the input calibration and validation of RELAP5 code. It was found that the inlet flow rate was overestimated by the code for high frequency oscillations due to the implementation of steady-state two-phase flow regime map in RELAP5 code. On the other hand, Fullmer et al. (2016) validated the RELAP5/MOD3.3 code for subcooled cooling, flashing, and condensation in a 4.5 m annulus test section in a pressure range of 0.18–0.95 MPa, a heat flux range of 55–265 kW/m², an inlet liquid subcooling range of 7–30 °C, and an average inlet liquid velocity range of 0.23–2.52 m/s. The comparison showed acceptable results in the 2.8 m heated section and noticeable disagreement along the 1.7 m unheated section (riser) for the condensation and flashing flow, which were significantly under-predicted by the RELAP5/MOD3.3 model.

In the current study, the RELAP/MOD3.2 code (Ransom et al., 1995) is used to simulate the startup transients including the flow instabilities in a natural circulation flow driven test facility simulating a BWR-type SMR. The RELAP5 results are then compared with experimental results to demonstrate simulation gaps. Section 2 presents the experimental test facility and instrumentation. Section 3 introduces the fundamental models and constitutive relations relevant to the modeling of the natural circulation flow instability. The RELAP5 nodalization and input calibration are described in Section 3. Section 4 presents the results and discussion. And key conclusions are summarized in Section 5.

2. Natural circulation test facility

A natural circulation (NC) experimental test facility was built to investigate the potential natural circulation flow instabilities at low pressure and low power conditions for the Purdue Novel Modular Reactor with an electric output of 50 MWe (Ishii et al., 2015; Wu et al., 2015, 2016). A three-level scaling methodology, which was developed by Ishii et al. (1996) for the scientific design of Purdue University Multi-Dimensional Integral Test Assembly (PUMA) for GE's SBWR, was used for the scaling design of the reactor pressure vessel (RPV) in the prototype. The dimensionless numbers derived from the drift-flux model (Ishii, 1977) were used to determine the kinematic and dynamic parameters in the test facility under the prototypic pressure condition (Ishii and Kataoka, 1984). The detailed scaling analyses of the test facility started from an ideally scaled facility based only on dimensionless numbers, and finally proceeded with an engineering scaled facility taking account of various limitations such as laboratory space, instrumentation needs, and available electric power (Shi, 2015). Fig. 1 shows

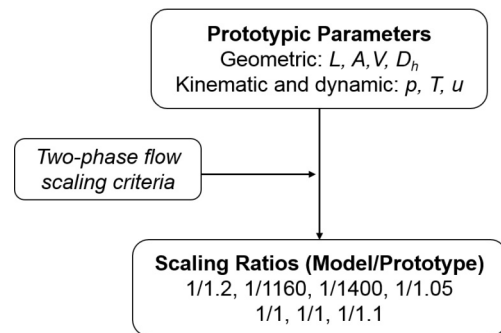


Fig. 1. Scaling ratios of the natural circulation test facility from NMR-50.

the scaling chart applying two-phase scaling criteria for the NC test facility. It is worthwhile emphasizing that this natural circulation test facility keeps a similar height to that of the prototype of NMR-50, which facilitates the investigation of the flashing induced flow instabilities due to the reduced hydrostatic head in the chimney section. Meanwhile, this test facility is significantly reduced in flow area and so is the volume due to the limits of heating power and lab space. Finally, the inlet flow velocity ratio, i.e., the natural circulation flow velocity ratio, between the test facility and the prototypic reactor is about 1/1.1.

This natural circulation test facility as shown in Fig. 2 composes of a four-channel heater section simulating NMR-50 reactor core, a chimney section (riser) above the core section, a simplified steam separator and steam dome, and a downcomer section. In addition, this test facility has a condenser at the top, a preheater to accurately control the inlet water temperature, a downcomer bypass line, and a circulation pump. It should be noted the circulation pump was only used for setting the initial water level. Table 1 summarizes important design parameters of the test facility (Shi et al., 2015a).

Regarding instrumentation, this test facility has three measurement ports distributed along the heated section and four in the chimney section. Each measurement port has an in-house impedance probe (IMP) to measure local area-averaged void fraction and a K-type thermocouple. Differential pressure transducers and absolute pressure transducers are installed to measure pressure differences at different locations and system pressure in the steam dome, respectively. The single-phase natural circulation flow velocity is measured at the core inlet flow velocity by using a Honeywell magnetic flow meter at the downcomer. Table 2 lists the instruments installed and their measuring uncertainties. Another key parameter to the test facility is the loop flow resistance, i.e., K factor, which determines the natural circulation flow rate with heater power. Here, the loop flow resistances were carefully designed to simulate the prototypic RPV. Particularly, the inlet flow resistance was controlled by a two-inch ball valve calibrated separately and integrally during shake down tests.

3. RELAP5 model and nodalization

The flow instabilities occurring in the natural circulation flow driven systems are complex phenomena to simulate at low pressure and low power conditions. Most dominant flow instability mechanism for NMR-50 is the flashing induced flow instability in the chimney section (Shi et al., 2015a, 2015b). The flashing induced flow instability involves thermal non-equilibrium phenomena, such as subcooled boiling in the core section, condensation at the outlet of the core section, and flashing in the chimney section. Liao and Lucas (2017) summarized the models for computational modeling of flashing flows. The most general and sophisticated

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