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Evaluation of distortion of wall stored energy in core make-up tank test facility

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ABSTRACT

Scaled-down thermal-hydraulic tests are widely used in nuclear reactor safety analysis. The wall stored energy is one of the inherent problems in a scaled-down test facility, which will cause distortions in the simulation of the transients or local thermal-hydraulic phenomena. In a scaled-down test facility for simulating the Core Make-up Tank (CMT) system, which is adopted as the passive safety system in AP series power plant, the cold wall functions as heat sink and absorbs heat from the hot liquid, thus affects energy balance. To study the influence of the wall stored energy on the CMT test facility, distortion evaluation on the CMT in the natural-circulation mode and drainage mode with H2TS method was analyzed. Then, numerical simulation model of CMT test facility was established using RELAP5/MOD 3.4, and sensitivity study of wall stored energy distortion was conducted. The distortion evaluation results show that even if the model wall thickness employs the geometric-similarity principle, there are distortions of the non-dimensional parameters because of the higher rate of heat transfer from the fluid to the wall and the smaller thermal inertia in the model. However, the evaluation of the wall stored energy distortion shows that in a certain range, the influence of the wall stored energy distortion can be neglected or is conservative. Therefore, through reasonable design and arrangement, the scaled-down CMT test facility can properly simulate the thermal-hydraulic phenomena of the prototype. The results provide a theoretical basis and guidance for the design and operation of the tests and lay the foundation for the construction of the test facility.

1. Background

Scaled-down thermal-hydraulic tests are widely used in nuclear reactor safety analysis to evaluate the reliability of the safety systems of nuclear power plants and validate thermal-hydraulic computer codes. For properly simulating various important thermal-hydraulic phenomena in different transient conditions, scaling analysis is a crucial method in the design of the test facility (Reyes and Hochreiter, 1998; Ishii and Kataoka, 1984; Yu and Choi, 2016; Sun et al., 2014), where the wall stored energy is one of the most concerned distortions. The wall stored energy refers to the heat stored in the metal. The prototype power plant operates in the steady state; thus, the temperature of the structural parts and metal boundary gradually becomes the same as the coolant temperature. In the loss of coolant accidents, the temperature of the reactor coolant decreases, with the system pressure decreases. The hot metal becomes a heat source, releasing heat to the coolant. Wall stored energy also exists in the scaled test facility, even if it has the same metal mass ratio and coolant mass ratio as the prototype, since the scaled test facility has larger specific surface areas. In this case, the metal releases heat more quickly and affects the steam production rate and thus the system pressure in the test facility (Wang et al., 2011a). Therefore, the wall stored energy exhibits a distortion, which affects the simulation results for the thermal-hydraulic phenomenon of the prototype.

The hierarchical two-tiered scaling analysis (H2TS) method developed by Zuber (1991) can be used to obtain the similarity criteria between the scaled test facility and the prototype. The H2TS methodology was practically used in the licensing application test of AP600 (Reyes and Hochreiter, 1998), where it obtained the similarity groups between the scaled test facility APEX and the prototype AP600. According to the report of AP600 issued in January 1995 (Reyes and Hochreiter), the wall stored energy caused distortions in APEX, and measurements were performed to mitigate this influence (Reyes et al., 2003). The excessive wall stored

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energy problem also caused distortions in ROSA (Nakamura et al., 2009) and SPES-2 (Medich et al., 1995), which are the other two integral test facilities of AP600 for licensing application. SPES-2 enlarged the flow area of the 4th-stage automatic depressurized system (ADS) by 270% to increase the energy-release ability for compensating the surplus wall stored energy (Bessette and di Marzo, 1999; Wulff et al., 1998).

Li et al. (2011) studied the release of stored energy in a scaling analysis through three different approaches—the differentiation method, control volume method, and integrated power method—according to the fundamental mechanism of heat transfer from the metal to the fluid within the pipe. The scaling analysis showed that the transient simulation of the stored-energy release could be achieved through carefully choosing the scale ratio of the diameter and the vessel thickness and fixing the facility height scale. For the engineering design, the integrated power method could be applied, and the geometric similarity in the wall thickness could be adopted. Using this method, the total energy released by the facility could be of a proper scale to the prototype, but the transient simulation cannot be satisfied.

The core make-up tank (CMT) is a crucial device of the passive core cooling system in the AP series pressurized water reactor nuclear power plants. In the prototype, the CMT is a vertical cylindrical vessel with hemispherical top and bottom end sockets (Schulz, 2006; Fuyun et al., 1999). A pressure balance line (PBL) connects the top of the CMT to a cold leg, which has a normally open isolating valve, so that the CMT is connected within the pressure boundary of the RCS system. However, the CMT has no heat insulation or heating functions, and the coolant temperature is equal to the environmental temperature. The discharge line is connected to the bottom of the CMT and equipped with isolating valves and the normally open check valves (Wang et al., 2011b, 2013). The diagram is shown in Fig. 1.

The CMT has two operation modes, natural circulation and drainage, which appear successively in the SBLOCA transient process. The first is the natural-circulation mode. The hot water or two-phase mixture from the main loop is circulated into the top of the CMT, and the cold water is drained from the bottom of the CMT. The second is the drainage mode. The vapor is injected into the top of the CMT, and the natural circulation stops. The metal wall of the CMT functions as a heat sink instead of the heat source. The cold wall absorbs heat from the hot water circulated into the CMT, resulting in thermal stratification, and then affects the driving force of the natural circulation. Similarly, in the drainage mode, the cold wall absorbs the heat released from the vapor condensation and affects the pressure, steam flow rate, and drainage flow rate (Yonomoto et al., 1997; Lee and No, 1998).

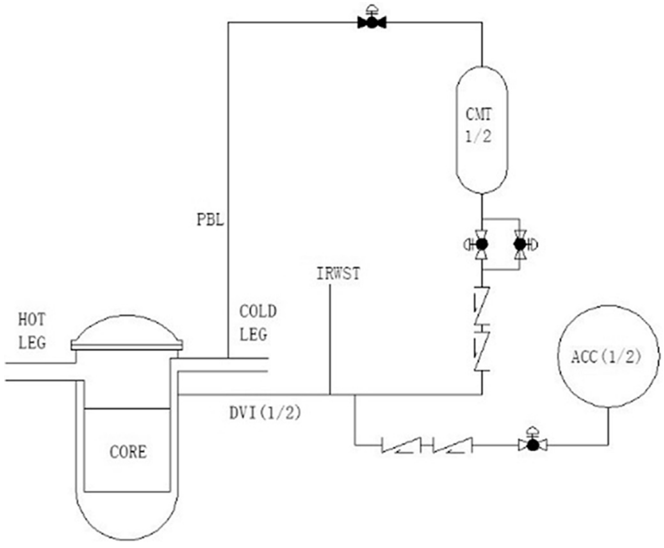

Fig. 1. Schematic of the CMT system loop.

Reyes and Hochreiter, 1998 and Deng et al. (2013) performed a scaling analysis of the CMT in the integral test facility and obtained the scale distortion of the non-dimensional parameters. They concluded that the dominant non-dimensional parameters matched well and the integral test facility properly represented the important phenomenon of the CMT and the process in the prototype nuclear plant. However, the wall stored energy distortion was not analyzed in detail.

Therefore, to verify that the scaled CMT test facility can simulate the transient process and safety-system response of the prototype properly, it is necessary to study the wall stored energy problem and try to preserve the release rate of the heat stored in the metal for satisfying the requirements of the scaling analysis. Moreover, it is necessary to analyze the influences of the wall stored energy distortion in these situations and evaluate the distortions.

The contents of this paper are as follows. The distortion evaluation of the CMT is presented in section 2, and the CMT system model with RELAP5/MOD 3.4 is presented in section 3. In sections 4 and 5, we report our sensitivity study of the wall stored energy in the natural-circulation mode and drainage mode and propose several guidelines for designing and operating the test facility.

2. Distortion evaluation

The distortion evaluation in this paper focused on the CMT behavior, therefore the reactor pressure vessel (RPV) is simplified as a boundary condition without any internal structures. The test facility in this analysis is designed with full temperature and full pressure as in the prototype. The height ratio between the test facility and the prototype is 1:1, the diameter ratio is 1:7.7, and the height ratio of the CMT container is 1:2. To perform the scaling analysis, the H2TS method is adopted (Reyes and Hochreiter, 1998; Ishii and Kataoka, 1984; Reyes and Hochreiter).

2.1. Natural-circulation mode

The CMT natural-circulation mode is dominated by the driving force and drag force because of the density difference between the cold water in the CMT and the hot water in the PBL. Driven by the density difference, the cold water in the CMT is injected into the DVI line, and hot water with a relatively low density enters from the PBL (Rabiee et al., 2016). The hot fluid from the PBL initially heats the cold wall of the CMT. Therefore, the heat-transfer phenomenon of the CMT wall in the natural-circulation mode should be considered. Thermal stratification occurs in the natural-circulation mode, and the natural-circulation flow rate gradually decreases during the heating of the CMT. When the PBL becomes void, it evolves into the drainage mode (Lee and No, 1997, 1998).

According to the WCAP14270 report (Reyes and Hochreiter) and Reyes and Hochreiter, (1998), in the natural-circulation mode, it can be assumed that the flow is single-phase and one-dimensional quasi-steady-state with linear variation of temperature, and the loss coefficient is independent of Reynolds number.

For the CMT system, non-dimensional mass equation:

$$\tau_{l,o}\frac{d}{dt}\left(\rho_l^+ V_l^+\right) = \varDelta\left(\rho_l^+ Q_l^+\right) \tag{1}$$

Non-dimensional momentum equation: