Steam Binding and Inhomogeneous Top Quenching Observed during ATLAS LBLOCA Reflood Tests

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1. Introduction

A set of reflood tests [1] has been performed by using ATLAS (Advanced Thermal-Hydraulic Test Loop for Accident Simulation) [2] which is a thermal-hydraulic integral effect test facility for the pressurized water reactors of APR1400 and OPR1000. Several important phenomena were observed during the ATLAS LBLOCA reflood tests. They include the phenomena of steam binding, inhomogeneous top quenching, ECC bypass, downcomer boiling and multi-dimensional behavior of ECC in downcomer annulus, etc. Among them the present paper discusses on two topics of steam binding and inhomogeneous top quenching.

2. Steam Binding

Figure 1 shows a schematic diagram of the steam binding phenomenon in the ATLAS primary system during the LBLOCA reflood tests.

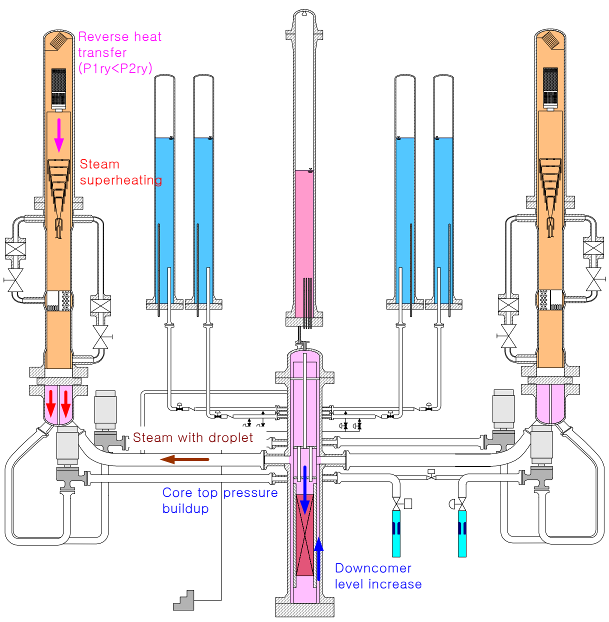

Figure 1 Schematic diagram of the steam binding phenomenon in the ATLAS

The steam binding is a thermal-hydraulic process which could limit the flow of coolant into the core. Some of the coolant leaves the core as liquid or entrained droplet, enters the upper plenum, passes through the hot legs and moves into the steam generators U-tubes. When the primary system pressure has decreased below the steam generator secondary pressure early in the accident, a reverse heat transfer begins to be activated from the steam generator secondary-side to the primary-side coolant flowing into the steam generator U-tubes. The increased resistance to the flow of steam to the break increases the upper plenum pressure. This phenomenon is known as 'steam binding'. The increased pressure at the top of the core relative to the broken-loop cold legs rapidly causes the water in the core to be pushed backward through the core into the lower plenum and then into the downcomer. Thus, the rapid increase in the downcomer level is caused by this steam binding phenomena which displaces the water in the core backwards into the downcomer.

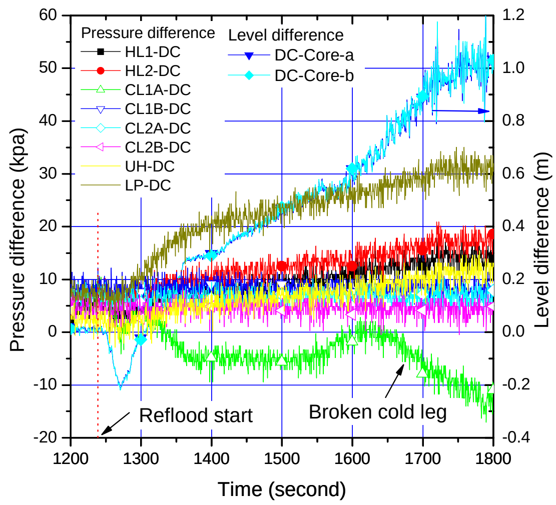

Figure 2 Behavior of pressure difference relative to downcomer and core-downcomer level difference

The thermal-hydraulic parameters of fluid temperature, flow rate and loop water level were analyzed to verify the fluid characteristics in the RCS loop and the reflux heat transfer from steam generator and steam binding phenomena in U-tube or intermediate legs were identified throughout the reflood tests.

Figure 2 shows the typical results showing the steam binding. The differential pressures between the other parts in the primary system and downcomer increase steadily throughout the test. The level difference is also increasing. The level reversal during initial 50 seconds is caused by the rapid vaporization of ECC in upper downcomer annulus. Even though the steam binding phenomena is observed during the test, its effects on core cooling behavior seem to be very little.

3. Inhomogeneous Top Quenching

During the reflood process the heater rod is quenched not only by the ECC injected from the core bottom but also by the accumulated water falling from the upper plenum to the core top, which are named as 'bottom quenching' and 'top quenching', respectively. The present concern is top quenching which shows radial in-homogeneity. The top quenching phenomena caused by a falling of the accumulated water at the upper plenum is responsible for this early quenching of the two upper clad temperatures. Accumulation of the water at the upper plenum is mainly due to a condensation of the superheated or saturated up-flow steam by contacting relatively cold upper head structures and a de-entrainment of the droplets, entrained from the near-downstream of the quench front by a decreasing steam velocity due to an enlarged flow area.

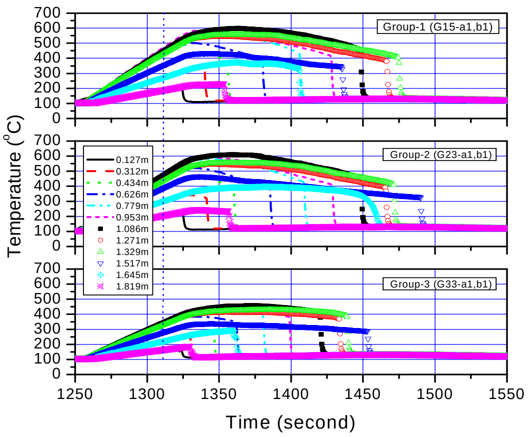

Figure 3 Axial surface temperature distributions of three core heater rods during LB-CL-14 (Group-1, 2 & 3)

Figure 3 presents the axial surface temperature distributions of three heater groups during the LB-CL-14 test. A top quenching phenomena was observed both in heater groups 1, 2 and 3, which was located in the center (Group-1), middle (Group-2) and outer (Group-3) regions of the core, respectively. During the LB-CL-14 test the top quenching phenomena occurred more quickly in Group-3 than in Group-1 and Group-2. It is due to the fact that the radial power distribution of the APR1400 is simulated and the initial powers per rod for the heater group 1, 2, and 3 are 2.438, 2.434, and 1.638 kW, respectively. However, the top quenching phenomena occurred more quickly in Group-2 than in Group-1 and -3 during the other cases of LB-CL-09 and LB-CL-11 tests where the uniform radial power is simulated. During the LB-CL-11 and LB-CL-14 tests the same power per rod was given to the heaters and their initial values were 2.623 and 2.129 kW, respectively.

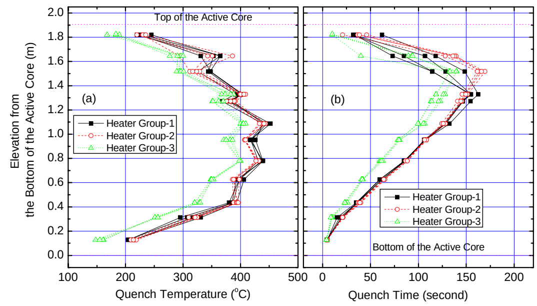

Figure 4 Behavior of quench temperatures and quench times along the axial elevation of the active core

Figure 4 shows the behavior of quench temperatures and quench times along the axial elevation of the active core during LB-CL-14. The quenching of the cladding is progressed from the lower part of the rods. However, as indicated in Fig. 4, early quenching phenomena can be observed at the upper third part of the active core region, especially at the height of 1.645, and 1.819 m above the active core bottom. In the LB-CL-14 test, quench times of Group-3 are shorter than those of Group-1 and -2 due to the applied radial power distribution, which is also shown in Fig.3.

4. Conclusion

The ATLAS facility could provide the unique data peculiar to APR1400. Two important thermal-hydraulic phenomena of steam binding and inhomogeneous top quenching were identified during the LBLOCA reflood tests by using the ATLAS. Inhomogeneous top quenching was changed for the different radial power profiles provided. Even though the steam binding phenomena was observed during the ATLAS reflood tests, its effects on the core cooling behavior seem to be very little.

REFERENCES

[1] Park, H.S., Choi, K.Y., Cho, S., et al., "An Integral Effect Test on the Reflood Period of a Large-Break LOCA for the APR1400 Using the ATLAS," Proceedings of ICAPP '08, Anaheim, CA USA, June 8-12 (2008).

[2] Baek, W. P., Song, C.H., Yun, B.J., et al., "KAERI Integral Effect Test Program and the ATLAS Design," Nuclear Technology 152, 183 (2005).