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Experimental Study of the APR+ Direct ECC Bypass in the Air-water Test Facility

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1. Introduction

The APR+ is an improved Korean Nuclear Power Reactor, which has been developed as a two loop evolutionary PWR (Pressure Water Reactor) with a number of advanced design features to enhance safety based on the APR-1400 technology [1]. The emergency core cooling system (ECC) of the APR+ is different with that of the APR-1400, though the APR+ adopted a direct vessel injection (DVI) system which is the same design features of the APR-14000. The main difference of the DVI+ is the emergency core barrel duct (ECBD) which is designed to increase the amount of the injection water to the core region. In addition, the DVI+ is the optimized design to enhance the performance considering the muliti-dimensional thermal-hydraulic behavior and the 4-emergency diesel generator (EDG) system applied to the APR+ [2]. The schematic of the DVI+ system is shown in Fig. 1.

The performance of the DVI system has been an important issues for past decades, and many researchers have studied the related thermal-hydraulic technical issues such as the ECC bypass fraction, the steam condensation effect, temperature distribution, sub-cooling margin, and etc [3-5]. However, the previous research cannot be directly applicable to the APR+ owing to the unique features of the DVI+. The current study will elaborate on the experimental evaluation of the direct ECC bypass performance. The 1/5 ECC bypass test facility which is designed with a linearly reduced 1/5 scale referring to the APR+ was used to investigate the effect of the DVI+ injection nozzle location and the broken cold leg velocity on the direct ECC bypass fraction. However, air is used as a working fluid to simulate the steam flow induced from the broken cold leg, and thus, the direct contact condensation effect is not considered in this study.

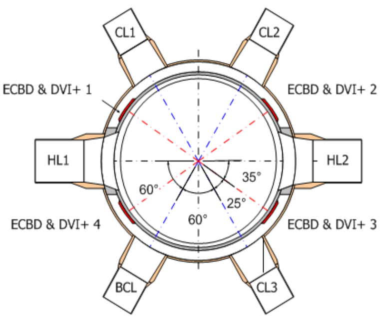

Fig. 1. DVI+ nozzles with ECBD of the APR+

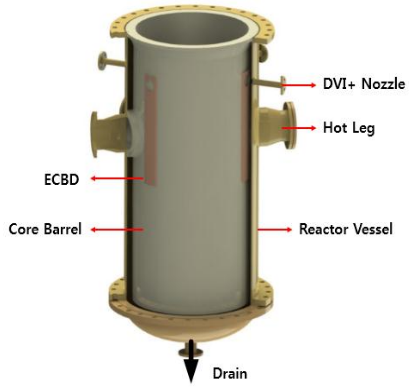

Fig. 2. Main test section of test facility

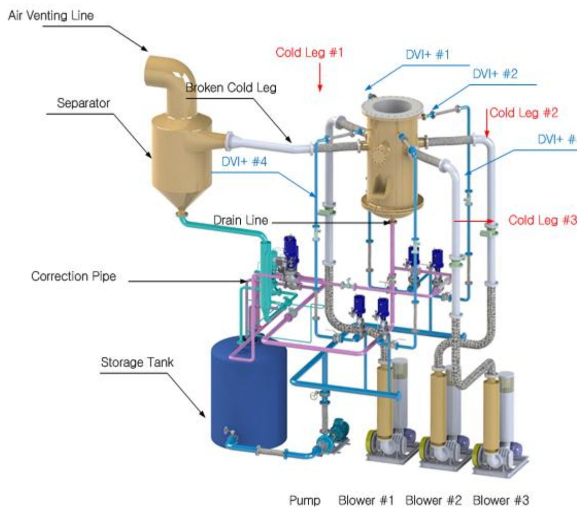

Fig. 3. Schematic of the 1/5 ECC bypass test facility

2. 1/5 Scale Experimental Test facility

The 1/5-Scale ECC bypass test facility were construed with a 1/5 linear scaling ratio to simulate the fluid flow phenomena at the downcomer region of the APR+ reactor. Main test section is shown in Fig. 2, and Four ECBD with DVI+ nozzles were attached the core barrel and the reactor vessel, respectively, to conserve similarity of the cross flow induced by broken cold leg. Basically, the downcomer region and the position of the DVI+ nozzles were simulated by preserving the geometric similarity. The test facility consists of the main test section, separating system, drain system, and reservoir tank as shown in Fig. 3. All of the system was constructed as a close loop to recirculate the coolant. The separating system was designed to simulate the broken cold leg, and the induced cross flow at the downcomer region was controlled by using three blowers. Total injection flow rates of the DVI+ were measured using vortex flow meters instrumented on the each DVI+ supply line, and thus, the bypass fraction can be easily calculated by measuring the mass flow rates in the separating or drain system.

3. Test results and discussion

The system pressure and the temperature were maintained at the atmosphere pressure and the room temperature, respectively. Test conditions for the DVI+ nozzle injection velocity was determined referring the APR+ reactor using a modified linear scaling method [5]. The ECC phenomena is totally different with the DVI injection mode, and thus, three different tests according to the injection mode were carried out; 1&4, 2&4, and 3&4 assuming the maintenance and the single failure considering APR+ 4-EDG-system. In addition, the air velocity was used as an independent test conditions since the direct ECC bypass phenomena is highly dependent on the circumferential momentum induced the air flow velocity at the downcomer region. All tests were carried out with maintaining low water level at the downcomer region to avoid the sweep out phenomena of the ECC injection.

One important phenomena of the ECC bypass phenomena is the amount of bounced back flow rate on the core barrel, and it depends on the ECBD internal gap which is designed to capture the sweep out flow rates. Therefore, except for the DVI+ nozzles, two different ECBD test sections were used to evaluate the internal gap effect on the ECC bypass fraction. One is the normal ECBD which having the internal gap obtained from a reduced linear scale of 1/5 referring to the APR, and the other one is the 20% reduced gap of the ECBD. Additional tests were also carried out without the ECBD as a reference test.

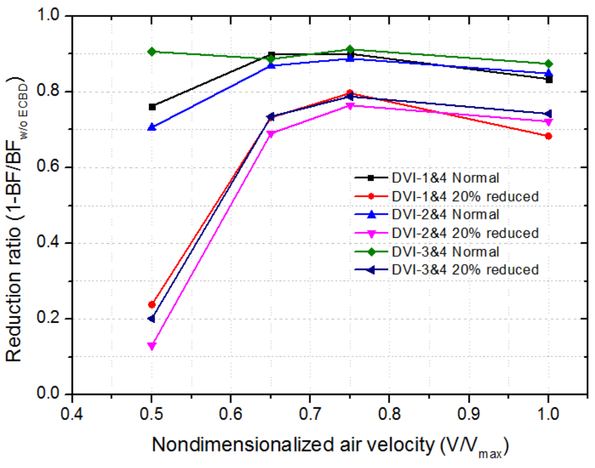

Fig. 5. Comparison of the bypass fraction with w/o ECBD

Figure 5 shows the whole test results for the DVI+ injection mode and the cold leg velocity. The x-axis the cold leg velocity divided by the maximum cold leg velocity, and the y-axis the bypass fraction ratio which shows the reduced bypass fraction compared with those of the reference tests. As shown in Fig. 5, the bypass fraction greatly reduced regardless of the injection modes and cold leg velocity, simultaneously.

In the case of the 1&4 injection mode, the DVI+ nozzles are located closely on the broken cold leg, and thus the test results showed the most large bypass fraction. For the two different ECBD test sections, the gap effect was significant on the ECC bypass fraction, since it is expected physically that the bounced-back flow rates is the majority of the bypass fraction. However, the overall bypass fraction for the DVI+ nozzles with the ECBD were greatly reduced compared with the reference cases.

4. Conclusion

Experimental study for the direct ECC bypass phenomena has been carryout out with various the injection mode and air velocity conditions. The tests were performed in the 1/5 scale ECC bypass test facility, and the test condition was defined using a scaling law referring to the APR+ reactor. Test results showed that the direct ECC bypass fraction was greatly enhanced compared with the reference test (w/o ECBD). The internal gap effect was also evaluated simply by changing the test section, though the direct ECC bypass phenomena accompanied complex multi-dimensional fluid flow. It is expected that the test results can be used for the validation of safety analysis, but it was also noted that the direct condensation effect between the coolant and steam was not considered in this study.

Acknowledgments

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