Experimental Investigation on Operational Performance of PAFS for CIV Opening Stroke

Seok Kim [a*], Byoung-Uhn Bae[a], Yusun Park[a], Kyoung-Ho Kang[a]
[a] *Korea Atomic Energy Research Institute, 111, Daedeok-daero 989Beon-Gil, Yuseong-Gu, Daejeon, 34057, KOREA*
[*] *Corresponding author: seokim@kaeri.re.kr*

1. Introduction

PAFS (Passive Auxiliary Feedwater System) is one of the advanced safety features adopted in the APR+ (Advanced Power Reactor Plus) which is intended to completely replace a conventional active auxiliary feedwater system. PAFS cools down the steam generator secondary side and eventually removes the decay heat from the reactor core by adopting a natural convection mechanism; i.e., condensing steam in nearly-horizontal U-tubes submerged inside the PCCT (Passive Condensation Cooling Tank). With an aim of validating the operational performance of PAFS, the experimental program of an integral effect test is in progress at KAERI (Korea Atomic Energy Research Institute). The test facility, ATLAS-PAFS was constructed to experimentally investigate the thermal hydraulic behavior in the primary and secondary systems of the APR+ during a transient when PAFS is actuated.

In this study, PAFS-CIV-01 test was performed for validating the cooling rate of the reactor according to the CIV opening stroke at the FLB accident, which was analyzed as the most severe case in the APR+ SSAR (Standard Safety Analysis Report). With an aim of simulating a FLB+CIV accident of the APR+ as realistically as possible, the three-level scaling methodology was taken into account to determine the test conditions of the steady-state and the transient. The main objectives of this test were not only to provide physical insight into the system response of the APR+ during changes of CIV opening stroke but also to produce an integral effect test data to validate a thermal hydraulic safety analysis code.

2. Experiments

2.1 Test Facility

A schematic diagram of ATLAS-PAFS is shown in Figure 1. It is composed of a steam-supply line, a condensation heat exchanger, a return-water line, and a PCCT (Passive Condensate Cooling Tank). The steam-supply and the return-water line connect the PCHX to the steam generator of the ATLAS. In order to preserve a pressure drop of the facility to a half of the prototype, the pipe size was determined to be 1-1/2" for the steam-supply line, and 1-1/4" for the return-water line. Each line includes an orifice and a coriolis mass flowmeter. In particular, the return-water line was designed to scale down the volume of the prototype for conserving the inventory of the coolant.

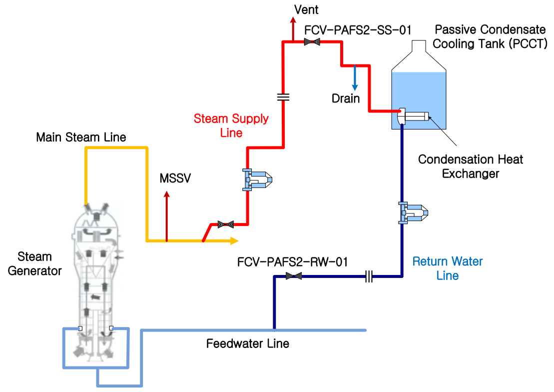


Fig. 1. Schematic diagram of ATLAS-PAFS.

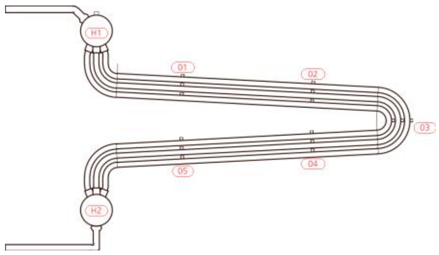


Fig. 2. Design of the PCHX (dimension in mm).

PCCT was designed as a rectangular pool, which has a half-height scale and a reduced area according to the global scaling ratio of the ATLAS. The PCCT is placed at the elevation of 17.3 m above the ground, which aims at conserving the level difference between the PCHX and the coolant surface in the SG-2. The PCHX is placed at the bottom region of the PCCT, where the center of the PCHX tube is 1.06 m above the PCCT bottom surface. When PAFS is actuated, heat transfer from the PCHX makes evaporation of the pool water in the PCCT, and the steam flows outside the building through a pipe on the top.

Figure 2 shows the design of the PCHX in the ATLAS-PAFS. The PCHX has three tubes which conserves the heat transfer rate at the surface according to the scaling methodology. A reduced diameter of the tube enabled the heat removal rate to be conserved in the facility. The tubes have the same material and the thickness to preserve the heat flux and the wall temperature. Top and bottom headers were designed to conserve the volume of the prototype. In order to prevent vibration of the PCHX tubes in the PCCT, the structure of the support bar was manufactured. On the inner wall and outer wall, the wall temperature was measured at five points along the tube length to estimate the wall heat flux and the heat transfer coefficient. Also, a fluid temperature profile inside the PCHX was measured by installation of the thermocouples in a vertical direction.

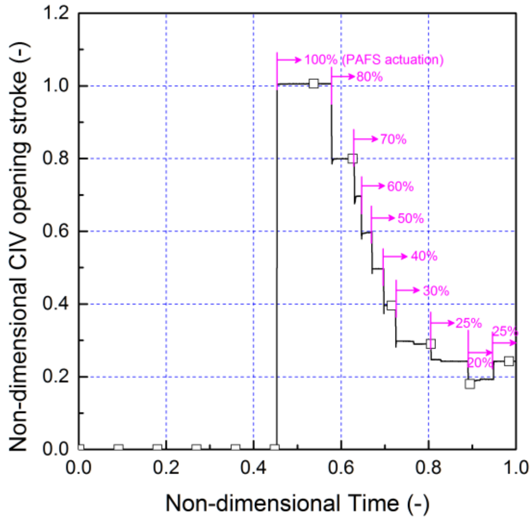


Fig. 3. Stoke changes of the CIV.

2.2 Test Conditions and Procedures

Prior to a main test, several actions should be taken to set proper initial and boundary conditions. They include an instrument calibration, purging and filling the ATLAS system including leakage tests, and an implementation of test-specific control logics into the process control computers for sequence control. The sequence control logics execute the required control actions for the corresponding control devices such as the main core heater, reactor coolant pump, SIP, and valves including the break valve and PAFS actuation valve. For the initial condition of the PAFS, the PCHX, the return-water line, and the PCCT were filled with the water of a room temperature. The collapsed water level in the PCCT was maintained to be 3.8 m according to the scaling methodology. When the whole system reached a specified initial condition for the test, as shown in Table 3.2, the steady-state conditions of the primary and the secondary systems were maintained for more than 30 minutes. After this steady-state period, the main test was started by opening the break simulation valve, OV-BS-07. Coincidently with the break, main feedwater pumps stopped and a main feedwater isolation signal (MFIS) was generated to close the main feedwater isolation valves (MFIVs). Reactor trip was induced by a LSGP (Low Steam Generator Pressure). Since the ATLAS facility had the maximum 10% capacity of the scaled full power and the actual pressurizer included a heat loss to the atmosphere, the reactor trip signal occurred by the LSGP, rather than the HPP (High Pressurizer Pressure).

When the reactor was tripped, both the RCP and the turbine were stopped coincidently. The main steam isolation valve (MSIV) of each steam generator was closed right after a LSGP signal. The water level of the

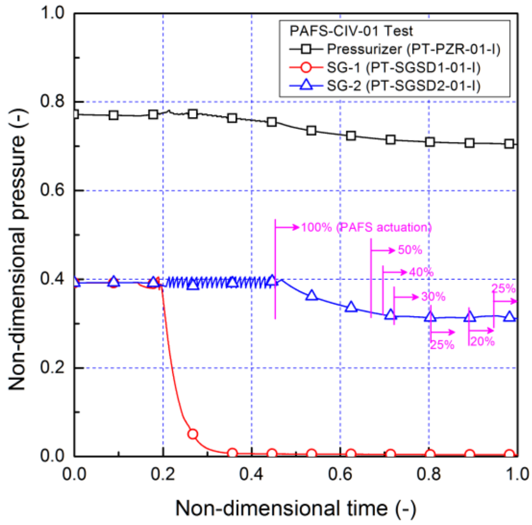


Fig. 4. Primary and secondary system pressure.

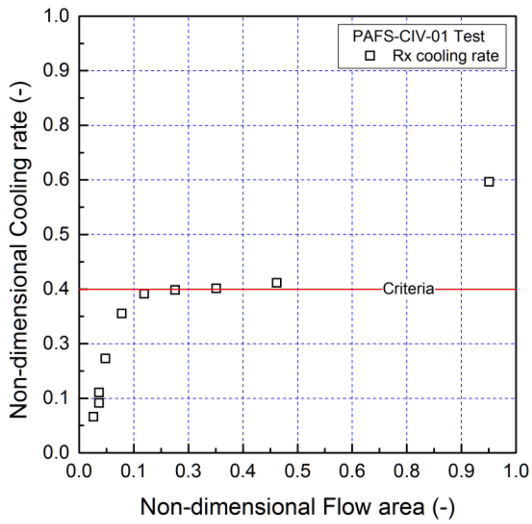
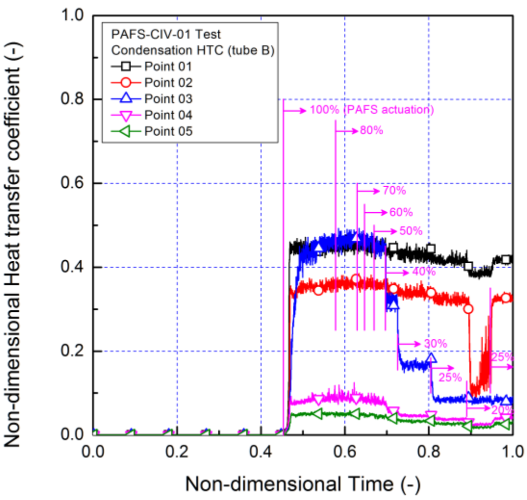


Fig. 5. Cooling rate of the core.

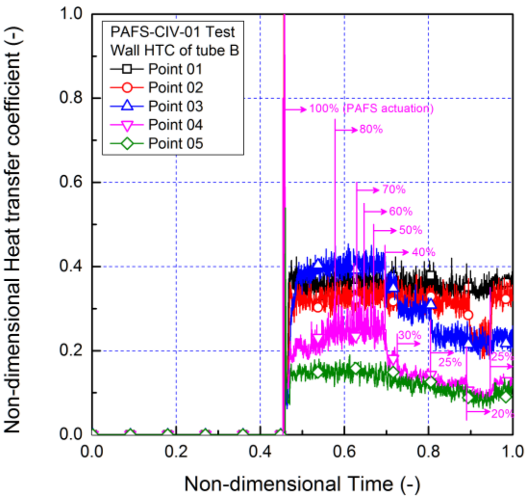
affected steam generator (SG-1) decreased rapidly to be empty due to the break flow. Contrary to the SG-1, the water level of the intact steam generator (SG-2) decreased continuously and reached the set-point of the passive auxiliary feedwater actuation signal (PAFAS), 25% of the WR water level. PAFAS opened the PAFS actuation valve (FCV-PAFS2-RW-01) on the return-water line and the heat removal by the natural convection of the PAFS was initiated on the SG-2. After the initiation of the PAFS, the stroke of the CIV was changed from 100% to 20% according to the sequence as shown in Figure 3.

2.2 Test Results

Figures 4 shows a pressure trend of the pressurizer and the steam generators. Coincidently with the break, main feedwater pump stopped and main feedwater was isolated. Due to a loss of the heat removal capacity by



(a) Inner wall



(b) Outer wall

Fig. 6. Heat transfer coefficient at the outer wall.

the secondary system, the pressure of the primary system increased during the initial period. After the actuation of the PAFS, the pressure of the intact steam generator (SG-2) was gradually decreased and maintained at low stroke range of the CIV. The pressure began to decrease when the stroke of the CIV was increased.

The cooling rate of the core in PAFS-CIV-01 test is shown in Figure 5. The cooling rate of the reactor core is 75 °F/hr by SCS entry condition from 30 minutes after the reactor trip. The cooling rate of the core under 60% stroke (70.4 mm^2) of the CIV met the criteria. From the present experimental result, it could be concluded that the cooling rate of the core was controlled by the CIV opening stroke when the APR+ PAFS was operating.

The heat transfer coefficient was calculated from the heat flux and the temperature distribution as presented in Figure 6 for the tube B. As the steam velocity was reduced along the tube length, the heat transfer coefficient of the lower part of the tube presented a smaller value than that of the upper part of the tube. The heat transfer coefficient was decreased with the decrease of the steam flow rate.

3. Conclusions

The initial steady-state conditions and the sequence of event in the FLB scenario for the APR+ were successfully simulated with the ATLAS-PAFS facility. In the present report, major thermal-hydraulic parameters such as the system pressures, the collapsed water levels, the core cooling rate, the break flow rate, and the condensate flow rate at the return-water line were investigated and discussed. Following the reactor trip induced by the LSGP signal, the coolant inventory of the secondary system of the intact steam generator was reduced by the repeated opening and closing of the MSSV. When the collapsed water level reached 25% of wide range, the PAFS was actuated to cool down the primary system by the heat transfer at the PCHX. The pressure and the temperature gradient of the primary system was reduced as the stroke of the CIV was decreased during the heat removal by PAFS operation. The mean temperature gradient of the core was reduced as the stroke of the CIV was decreased. The cooling rate of the core under 60% stroke (70.4 mm2) of the CIV met the criteria. The water in the PCCT was heated up to the saturation condition by the heat transfer from the PCHX tube surface. In PAFS-CIV-01 test, the major sequence of events was ended before the water level decrease in the PCCT. From the present experimental result, it could be concluded that the cooling rate of the core was controlled by the adjustment of the CIV opening stroke when the APR+ PAFS was operating. This integral effect test data will be used to evaluate the prediction capability of existing safety analysis codes such as MARS-KS or SPACE codes and to identify any code deficiency with an operation of PAFS..

ACKNOWLEDGMENTS

This research has been performed as a part of the nuclear R&D program supported by the Ministry of Knowledge Economy of the Korean government.

REFERENCES

[1] K.H. Kang, S.K. Moon, H.S. Park, S. Cho, K.Y. Choi, B.J. Yun, T.S. Kwon, S.J. Yi, C.K. Park, B.D. Kim, Y.S. Kim, C. H. Song, and W.P.Baek, "Detailed Description Report of ATLAS facility and Instrumentation," KAERI/TR-4316/2011, Korea Atomic Energy Research Institute (2011).

[2] K. H. Kang, et al. "Separate and Integral Effect Tests for Validation of Cooling and Operational Performance of the APR+ Passive Auxiliary Feedwater System," Nuclear Engineering and Technology, Vol. 44, No. 6, August 2012.

[3] B.U. Bae et al.," Design Report of the Integral Effect Test Facility for the Passive Auxiliary Feedwater System (ATLAS-PAFS)", KAERI/TR-4756/2012 (2012).