Integral effect test on operational performance of PAFS for long term cooling

Yusun Park[1*], Byoung-Uhn Bae[1], Seok Kim[1], Kyoung-Ho Kang[1]
[1]*Thermal Hydraulics Safety Research Division, Korea Atomic Energy Research Institute*
111, Daedeok-daero 989, Yuseong-gu, Daejeon, 305-333, Republic of Korea
**Corresponding author: yusunpark@kaeri.re.kr*

1. Introduction

An integral effect test for long term cooling performance of the PAFS (PAFS-LTC-01) was performed with the ATLAS (Advanced Thermal-Hydraulic Test Loop for Accident Simulation) – PAFS (Passive Auxiliary Feedwater System) facility by KAERI (Korea Atomic Energy Research Institute).

The PAFS-LTC-01 test was performed for evaluating the cooling performance of the PAFS under the SBO condition. The ATLAS-PAFS was operated till the water level of the PCCT was decreased right above the PCHX. With an aim of simulating a SBO accident with the PAFS operation of the APR+ as realistically as possible, a pertinent scaling approach was taken.

The main objectives of this test were not only to provide physical insight into the system response of the APR+ during the long term operation of the PAFS but also to produce an integral effect test data to validate a thermal hydraulic safety analysis code.

2. Description of the ATLAS-PAFS

The ATLAS facility includes a reactor pressure vessel, two steam generators, four reactor coolant pumps, a pressurizer, and four safety injection tanks as shown in Fig. 1. The detailed ATLAS design, description of the signal processing system and control system of the ATLAS can be found in the literature [1].

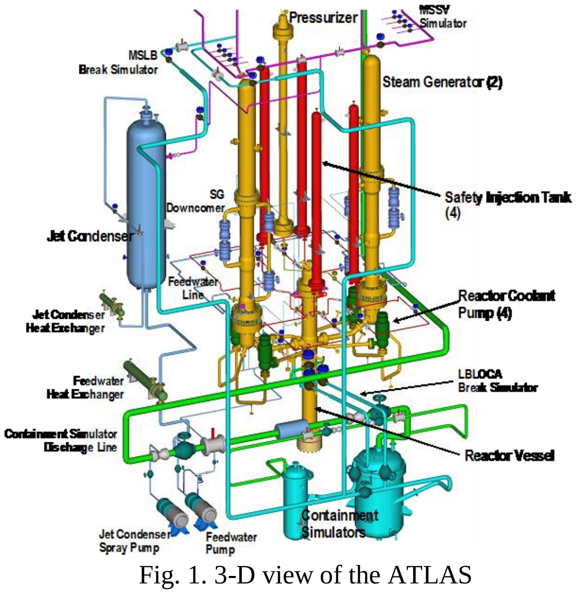

Fig. 1. 3-D view of the ATLAS

The PAFS is connected to the SG-2 of the ATLAS. The PAFS is composed of the PCHX, the PCCT, the steam-supply line, and the return-water line as shown in Fig. 2.

The PCHX has three tubes which conserves the heat transfer rate at the surface according to the scaling methodology. 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 PCHX is placed at the bottom region of the PCCT. The steam-supply and the return-water line connect the PCHX to the steam generator of the ATLAS. The detailed description of the ATLAS-PAFS test facility can be found in the literature [2].

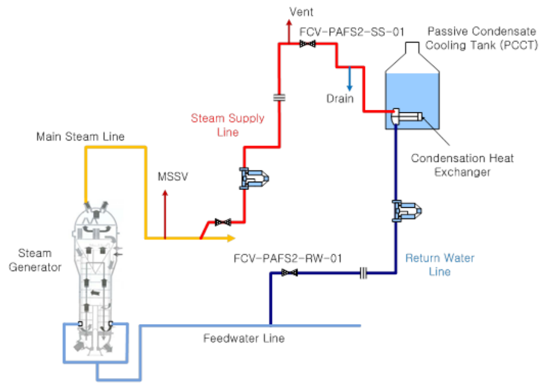

Fig. 2. Configuration of the ATLAS-PAFS

3. Experimental conditions

3.1 Decay power

As the SBO accident scenario starts, the core power starts to decrease along with the decay heat curve. The decay heat curve data of APR+ was obtained from the code simulation result based on the ANS 5.1-1973. The initial core power at the start of the transient was calculated 18.76 MW when the scaling ratio of the ATLAS to the PAR+ was applied to that decay heat curve date. Because the maximum core power of the ATLAS is about 2.0 MW, the heater power at the initial steady state was set to 1.50 MW. The heater power was then controlled to follow the specified decay curve after the reactor trip.

3.2 Water level of the PCCT

It was assumed that the heat transfer of PAFS will decrease when the upper header of the PCHX is exposed to the atmosphere. Thus, the inventory of PCCT water above of the bottom of an upper header is considered for the volume scaling of the ATLAS to the PAR+. With the consideration of the height from the PCCT bottom to the upper header bottom, the initial water level of the PCCT is calculated 4.15(m) from the PCCT bottom. In this experimental study, the initial water level of PCCT was set to 3.81(m) which is the nominal condition.

3.3Determination of test condition

The present test conditions were determined by a pre-test calculation with a best-estimate thermal-hydraulic safety analysis code, MARS. First of all, a transient calculation was performed with given power decay curve of the APR+ to obtain the reference initial and boundary conditions. A best-estimate safety analysis methodology was applied to the transient calculation of the APR+. The initial and boundary conditions for the present test were obtained by applying the scaling ratios to the MARS calculation results for the APR+. Actual initial conditions of PAFS-LTC-01 test were also summarized in Table Ⅰ.

4. Test procedure

When the whole system reached a specified initial condition for the test, as shown in Table Ⅱ, the steady-state conditions of the primary and the secondary systems were maintained for more than 30 minutes.

Table Ⅰ: Initial and boundary conditions

Design parameters	Target values	PAFS-LTC-01 test	Standard deviation
Normal power (MWt)	1.501	1.5866	0.0008
Pressurizer pressure (MPa)	15.44	15.48	0.007
Core inlet Temperature(^oC)	290.7	290.16	0.1386
Core outlet temperature (^oC)	326	325.38	0.1352
Pressurizer level (ml)	-	3.7547	0.0090
Steam pressure (MPa)	7.81	7.82 7.82	0.0007 0.0006
Steam temperature (^oC)	293.3	295.14 295.35	0.0930 0.0606
Steam flow rate (kg/s)	0.4277	0.3730 0.4106	0.0005 0.0009
Feedwater flow Rate (kg/s)	0.4277	0.3805 0.0361 0.3748 0.0345	0.0005 0.0005 0.0005 0.0006
Feedwater temperature (^oC)	232.2	234.59 233.86	0.0924 0.1187
SG water level (m, WR)	5.0	5.0159 5.0520	0.0060 0.0080
Hot leg flow (kg/s)	3.428	3.6518 3.7683	0.0329 0.0169
Hot leg temperature (^oC)	326	325.43 326.42	0.1664 0.0903
Cold leg flow (kg/s)	1.714	1.7117 1.9401 1.9336 1.8347	0.0213 0.0444 0.0139 0.0198
Cold leg temperature (^oC)	290.7	291.13 289.77 289.57 290.16	0.1377 0.1123 0.1075 0.1386

After this steady-state period, the main test was started by the actuation signal of SBO. Coincidently with the SBO start signal, the reactor trip was induced and several action of each component were accompanied as described in Table Ⅱ.

When the water level of SG2 reached the set-point of the passive auxiliary feedwater actuation signal (PAFAS), the PAFS actuation valve (FCV-PAFS2-RW-01) on the return-water line opened and the heat removal by the natural convection of the PAFS was initiated on the SG-2.

As the heat transferred from the system to the PCCT through the PCHX, temperature of the water in the PCCT increased and the collapsed water level in the PCCT started to decrease by boiling. Finally, the collapsed water level in the PCCT reached to the right above the upper head of PCHX where the termination point of test.

Table Ⅱ: Sequence of event

Event	Time after Break(sec)	Remarks (Set-point)
SBO start	0	
Reactor trip	0	Decay power control, Coincidently with SBO Start
Turbine / RCP Trips	0	Coincidently with SBO Start
MFIV, MSIV Close	0	Coincidently with SBO Start
First open of MSSV	3	7.7 MPa < PT-SGSD1/2-01 < 8.1 MPa
PAFS Actuation	2146	SG2 WR Level 25% (LT-SGSDRS2-01= 2.78m)
PCCT Level decrease	7500	Max. PCCT Level 4.1(m)
End of Test	107223	PCCT Level 0.95 (m)

5. Results and discussion

Fig. 3 shows a pressure trend of the pressurizer and the steam generators. After SBO starts, pressures oscillated by opening of MSSVs and the system pressures decreased continuously with operation of PAFS. The collapsed water levels of RPV are shown in Fig. 4. After 20 hours from SBO starts, thermal hydraulic behaviors of the system showed instabilities due to the dramatic degradation of the heat removal performance of PAFS.

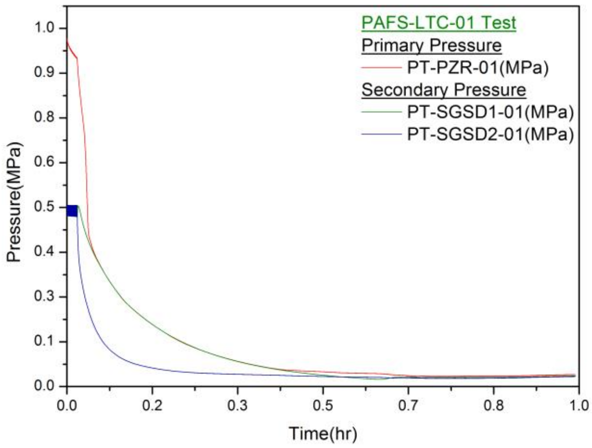

Fig. 3. Variation of the system pressure

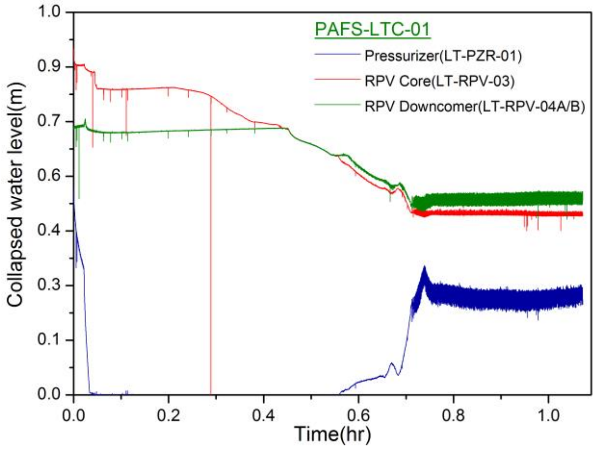

Fig. 4. Collapsed water levels in the primary side

Mass flow rate in the steam-supply line and the return-water line in the PAFS was shown in Fig. 5. After the drainage of the coolant in the return-water line and the PCHX (initial peak of the flow rate in the return-water line), the natural circulation flow in the steam-supply line and the return-water line was formed until the end of the transient. During this period, any kind of flow instability in the PAFS loop was not be observed. However, after 20 hours from the SBO starts, flow rates of the steam-supply line and the return-water line oscillated and it was obvious around 27 hours. This is the time when the water level of PCCT decreased to the upper head of PCHX and the heat removal performance of PAFS decreased dramatically.

The variation of collapsed water level in the PCCT is shown in Fig. 6. The collapsed water level of PCCT at the initial steady state was 3.8 (m). It increased up to 4.025(m) by volume expansion due to the heat transferred from the system to PCCT through PCHX as PAFS operated and started to decrease by boiling. It took about 25 hours to deteriorate the cooling performance of PAFS and 30 hours to decrease the collapsed water level of PCCT to the bending point of PCHX.

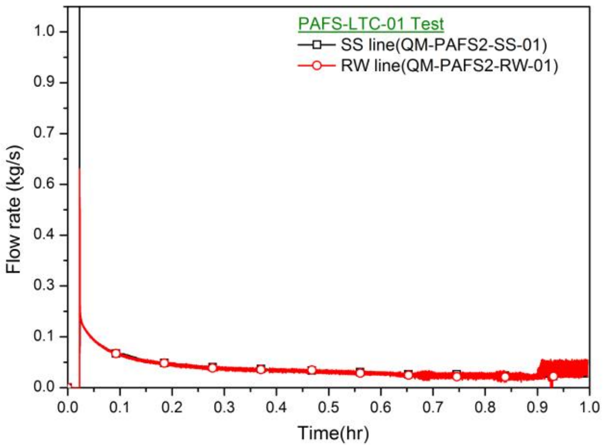

Fig. 5. Flow rates of the SS and RW line

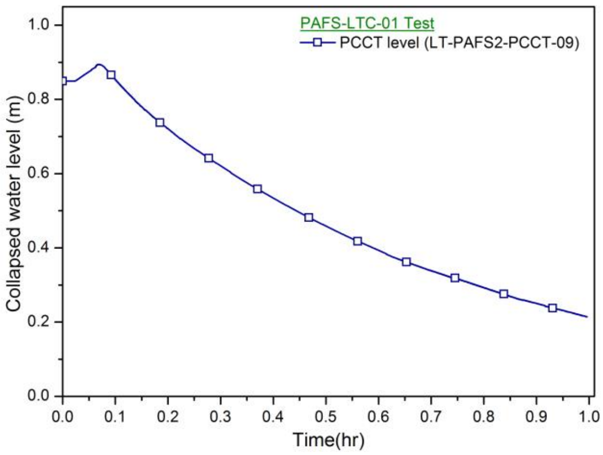

Fig. 6. Collapsed water level in the PCCT

Fig. 7 compared a wall heat flux on the outer surface of the PCHX tube B, which was calculated from the difference between the inner and outer wall temperatures. At points located near the PCHX inlet, the largest wall heat flux was observed due to the contact of the steam flow with a high temperature. The heat flux became zero after 25 hours due to the disappearing of temperature difference between inner wall and outer wall of PCHX.

If we assume that the collapsed water level of PCCT at the initial steady state was 4.15(m) as mentioned in the section 3.2, it takes about 44.4 hours as plant time scale to decrease the cooling performance of PAFS dramatically.

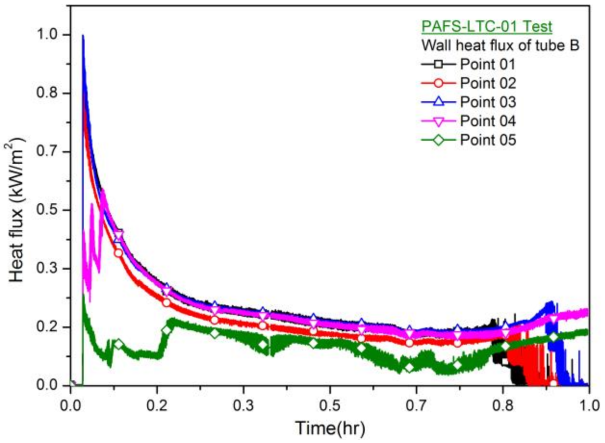

Fig. 7. Wall heat flux of tube B

6. Conclusion

PAFS-LTC-01 test was performed with ATLAS-PAFS facility for evaluating the cooling performance of the PAFS under the SBO condition. With the given decay heat curve data of APR+ which was obtained from the code simulation result based on the ANS 5.1-1973 curve, the ATLAS-PAFS was operated until the water level of the PCCT was decreased so that the PCHX is exposed to the air.

From the present experimental result, it was observed that the cooling rate of the core was reduced as PAFS operates during long time. The maximum limit that PAFS retains its cooling capability was until the time that the collapsed water level of PCCT reduced to the bending point of PCHX. It took about 30 hours in ATLAS-PAFS test which corresponds to 42.4 hours in the power plant with consideration of time scaling ratio.

REFERENCES

[1] K.H. Kang et al., "Revised Description Report of ATLAS facility and Instrumentation," KAERI/TR-5974/2015, Korea Atomic Energy Research Institute (2015).

[2] 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).