Experiments of Aerosol Removal with Various Submergence in Steam Generator

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1. Introduction

The steam generator is the primary route of radioactive materials releasing to environment when a steam generator tube ruptures (SGTR). Especially, a severe accident with the SGTR increases the amount of the fission product release, threatening the public health. The recent legislation for severe accident in Korea, therefore, set the quantitative goal of fission product release to protect the public from excessive radiological exposures.

We has been conducted the experimental studies about the aerosol removal in the SG of Korean NPP experimentally by the AEOLUS facility built in KAERI [1]. The results were used to estimate the realistic fission product behavior during the SGTR with severe accidents.

In this paper, we discuss the new results of integral tests recently performed with AEOLUS. The experiments includes the integral effects of steam driers and separators, with respect to the various submergence level in SG.

2. Experimental Facility

Figure 1 shows the schematic of the AEOLUS (Aerosol Experiments on LWR under SGTR) facility used for the tests. The detailed explanation about the basic AEOLUS facility is described elsewhere [1]. On top of the previous AEOLUS facility, we added the separator and the drier module for the integral test including the effects of them. Also, the long tube bundle was installed in the vessel whereas only the single tube and the short tube bundle were used for the previous tests.

Figure 2 shows the installation of separators and driers into the AEOLUS. The separator module and the drier plate are the same model as those in operating NPPs. However, the number of the separator and the area of drier plates are determined considering the scaling of AEOLUS versus the actual SG in NPP. To install the separator and drier, the pressure vessel was also extended with upper shells.

The SiO_2 particles with mass mean diameter (MMD) of 0.7 μm were used to simulate the insoluble fission aerosol. The SiO_2 particles were dispersed in ethanol with 10% wt., and the fluid were ejected into the mixing chamber with hot carrier gas. Then the ethanol evaporates in the hot mixing chamber and then the SiO_2 particles disperse in the carrier gas as aerosols.

The aerosol sampling systems were installed at the test facility to measure the aerosol concentration density at each position. Two different kinds of sampling system were used for the tests, the glass fiber filter system and the electrical low pressure impactor (ELPI, DEKATI). There are four different sampling positions which are the upstream (U), the inlet nozzle (N), the vessel (V), and the downstream (D). The filter sampling systems were installed at all four sampling points, and two ELPIs were installed at U and D.

The gas mass flow through the filter were measured using mass flow controller (MFC, Bronkhorst). Then, the aerosol concentrations were calculated from the aerosol mass collected in the filter divided by the integrated volume flow through the MFC. The ELPIs measured the aerosol number or mass with respect to the size, by using multiple impactor stages. Single or double stage diluter was connected in front of the ELPI to reduce the aerosol concentration down to the range of ELPI.

The aerosol mass at each position were calculated by subtracting the mass of clean filter, gasket, and filter holder from the mass of those after the sampling. The mass of each specimen was measured with the ultra-precision scale having minimum resolution of 0.1 μg. The actual resolution of the scale, however, is much less than that, mainly because of the accumulated uncertainties of repeated measurement. The minimum value of the measurement was determined from the uncertainty calculation and an engineering judgement.

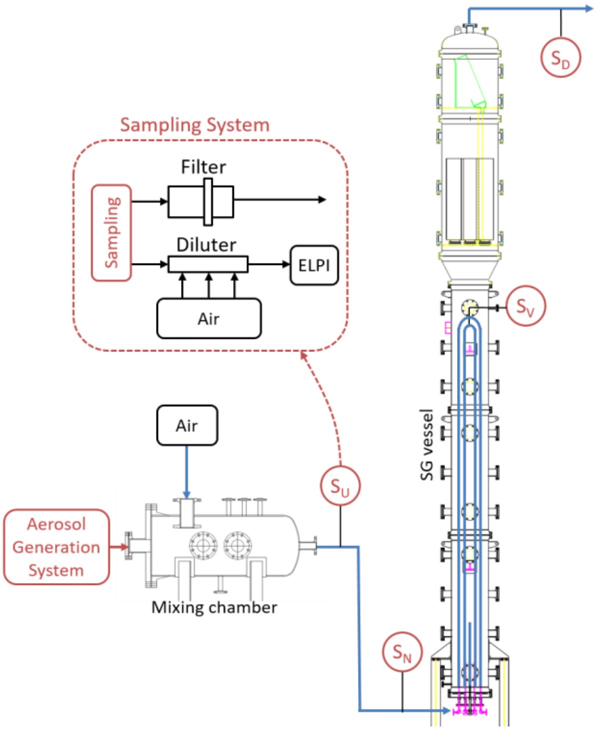

Fig. 1 Schematic of AEOLUS Facility

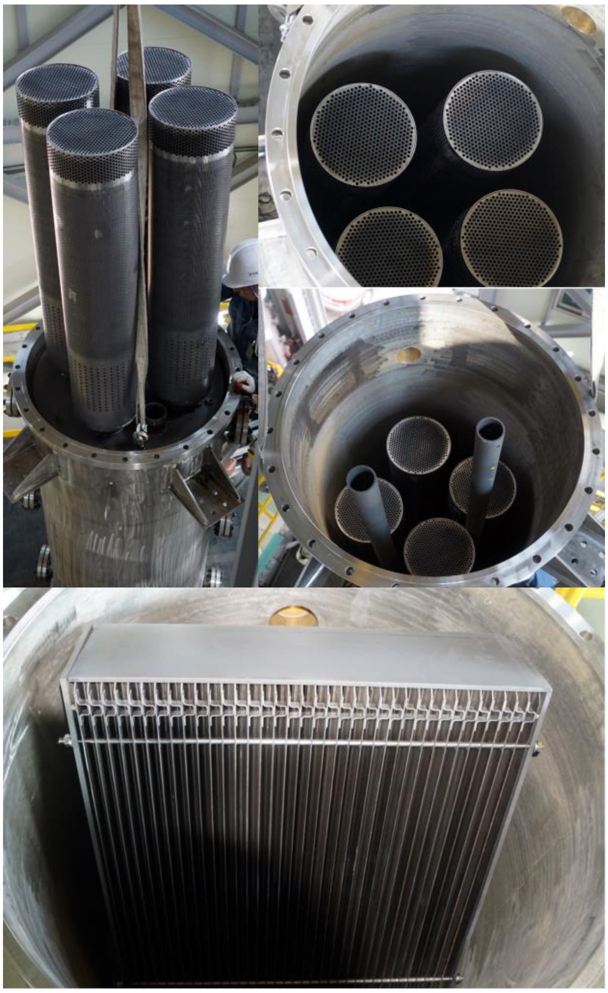

Fig. 2 Installation of Seperators and Driers on AEOLUS

3. Experimental Condition

Table 1 shows the test matrix conducted with AEOLUS facility. We conducted four integral tests, AFL01 to AFL04, where the AFL denotes aerosol-flooded-long bundle test. All the tests were conducted in flooded conditions with different submergences. The submergence decreases slowly by time due to the evaporation, however, the water is not filled during the sampling to remove the perturbation of the experimental condition by water injection. The submergence in Table 1 is therefore averaged values.

Table 2 shows the common thermal-hydraulic parameters of the tests. The carrier gas was air instead of steam to neglect the aerosol removal by the condensation, resulting in more conservative removal of aerosol in pools. The pressure at the primary side, which is upstream of the tube were about 6.9 bar abs and the pressure at downstream were about 2.3 bar. In those conditions, the flow at the broken tube were in choked condition. The mass flow rate of the air were about 0.17 kg/s and the gas temperature at the upstream were about 160^{o}C. The carrier gas were heated by the steam heater and by the wall of the vessel and the pipes which are electrically heated. The heater temperatures of the

Table 1 Submergence Level of Tests

Experiments	1^{st} sampling	2^{nd} sampling
AFL01	0.5 m	0.5 m
AFL02	0.5 m	0.5 m
AFL03	3.5 m	2.5 m
AFL04	2.0 m	2.0 m

Table 2 Common Experimental Parameters

Variable	Value
Working fluid	Air
Upstream pressure (bar)	6.9
Downstream pressure (bar)	2.3
Inlet gas temperature (^{o}C)	~160
Mass flow rate (kg/s)	0.17
Water level in vessel (m)	Varies by tests
Water temperature (^{o}C)	60

downstream pipe walls were set to be the same as the upstream ones, however, the temperature becomes lower because of the water temperature in the vessel, which is about 60 ^{o}C.

Figure 3 shows the tube used for the experiments, where the main carrier gas exit through the opening. The circumferential opening simulates the Guillotine break with the area same as the inner cross-section of the pipe. The tube is then inserted between the long tube bundle with the same pitch of the other tubes.

In every tests, the aerosol sampling was conducted twice, for 1 hours per each. The submergence of the sampling were kept constant for the tests, except the AFL03 where the submergence were decreased in 2^{nd} sampling. In the 1^{st} sampling of AFL03, the water in the vessel was overflowed to the aerosol sampling port of the vessel (V), therefore the level was reduced in 2^{nd} sampling.

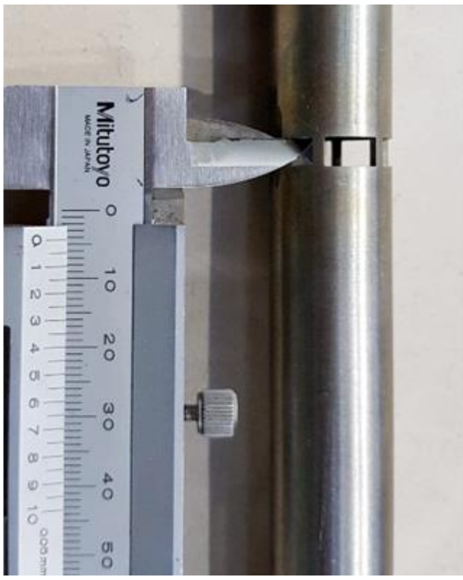

Fig. 3 Tube nozzle simulating Guillotine break

4. Experimental Results

Before estimating the decontamination factor (DF) of the tests, the minimum value of the aerosol measurement was determined. Since the DF is defined as the inlet aerosol concentration divided by the outlet concentration, the DF is affected a lot when the outlet concentration is very small. The minimum measurement value at the outlet, the downstream (D) in the tests, was estimated to be 0.1 mg from the RMS of repeated measurements of the aerosol specimen including unknown errors.

Table 3 shows the decontamination factor (DF) of the tests based on the aerosol concentration at each position. The concentration at the vessel (V) is set as the reference value to calculate the DF because the position is the inlet of the SG vessel. When the aerosol mass at the downstream is smaller than the minimum value of 0.1 mg, the decontamination factor was expressed such that the DF is larger than the value which is calculated with the downstream concentration of 0.1 mg.

The DF at the exit of the facility is DF(N-D), increasing generally as the submergence increases. The DF with the submergence of 2.5 m seems higher than that with 3.5 m, however, is because the inlet concentration is higher at the test with 2.5 m and the downstream concentration for the DF calculation were set as the minimum value of 0.1 mg. Among the DF values, that of the first sampling of AFL01 tests was 70, which is different from the other DFs with the submergence of 0.5 m. In that case, the aerosol generation efficiency was too low, therefore the data was excluded from further data processing.

Although we measured the aerosol concentration at the vessel, the concentration was not credible due to the extremely small bulk velocity and the small sampling flow rate. Also, the aerosol sampling failed at the vessel when the water level is 3.5 because of the overflow of the water into the sampling port.

Figure 4 shows the DF of the tests versus the submergence. The figure shows that the DF increases as the submergence increases, and then saturates when the submergence reaches at some level. It should be noted that the DF at 2.5 and 3.5 m is the lower bound of DF because the aerosol mass at the downstream are less than the minimum.

Table 3 Decontamination Factor of Tests

Test	Submergence (m)	DF	
		N-V	N-D
AFL01	0.5	7.7	70
	0.5	31	176
AFL02	0.5	42	181
	0.5	38	166
AFL03	3.5	Fail	>3575
	2.5	26	>4989
AFL04	1.5	133	1732
	1.5	>4420	789

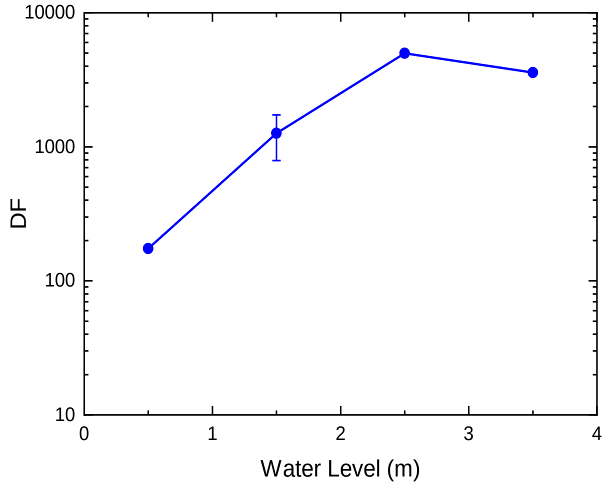

Fig. 4 Decontamination Factor by Submergence

Table 4 shows the DF values from ARTIST phase V, which are the aerosol removal tests in SG under flooded condition [2]. The ARTIST tests are similar to our tests, however, has different designs and experimental conditions. For example, the ARTIST phase V tests are conducted without the separator and the dryer modules and used N_2 as the carrier gas whereas we used air .

Our 0.5 m submergence tests of AFL01 and AFL02 are comparable to the E09 and E10 tests because they are similar in mass flow rate. But they are different in aerosol size and also different in inlet pressure. Also, the conditions such as temperatures and the inlet aerosol concentration are different from that of AFL tests, but they are not described in detail. The DF values of AFL tests are much smaller than those of the ARTIST tests. altough the lower DF of AFL tests are corresponds to the trend of ARTIST test, such that the smaller aerosol size reduces the DF. Still, the DF values of AFL tests are far smaller than ARTIST tests. The other possible explanation is that the temperatures of ARTIST tests are much lower than that of AFL tests. The inlet temperatures of ARTIST tests are about 91°C and the water temperature are 28°C, whereas those of the AFL tests are 160 °C and 60 °C, respectively. The lower temperature reduces the evaporation of water at the pool surface, reducing the aerosol escape from the water surface. The effect of submergence on DF was not found in ARTIST phase V tests.

Table 4 Decontamination Factor of ARTIST Phase V

Test	Submergence (m)	AMMD (μm)	Mass flow (kg/h)	Inlet Press. (bar)	DF
E07	0.56	1.4	50	1.12	53
E08	0.56	3.7	50	1.12	1370
E09	0.58	1.4	620	4.93	1210
E10	0.56	3.7	619	4.93	2780
AFLs	0.5~3.5	0.7	612	6.9	

5. Summary

The aerosol removal in steam generator with different submergence in the vessel were tested with integral AEOLUS facility. The long tube bundle resembling the SG tubes in Korean NPP was inserted in the vessel, and the separator and the drier were installed on top of the vessel. The SiO2 particles of MMD = 0.7μm were dispersed in hot air and the flow blew into the vessel with a choked flow condition. The submergence in the SG vessel were varied from 0.5 m to 3.5 m to test the effect of that to the DF.

The results show the DF increasing as the increase o submergence, and saturating when the level is deeper than 2.5 m. With the submergence larger than 2.5 m, the aerosol mass at the downstream was smaller than the minimum credible value of measurement, 0.1mg. Therefore, the DF values at those submergences were expressed such that the DF is larger than the certain value calculated with the minimum mass at downstream.

The DFs from the test were then compared with the results from ARTIST phase V, and they showed corresponding trend of DF decrease by higher submergence. However, the DF value of the tests were much smaller than those of ARTIST tests although the other conditions such as the experimental temperatures can contribute the difference of the results.

Acknowledgement

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