Aerosol Removal Experiment in Steam Generator simulating Tube Rupture Event

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1. Introduction

The steam generator tube rupture (SGTR) event is an event which causes the radioactive materials in primary coolant releasing to the secondary side bypassing containment. Especially, in severe accident condition accompanying core melting, large amount of fission product in primary coolant releases through the main steam safety valves (MSSVs) or atmospheric dump valves (ADVs). In SGTR event, the steam generator itself becomes a primary device removing the radioactive materials. Therefore, the characteristics of radioactive material removal in steam generator is required to be tested to estimate the radiological consequences by SGTR properly.

In this paper, the aerosol removal in steam generator was tested experimentally for single tube when the steam generator is dry or flooded. The experimental procedures are introduced and the results are discussed. Planned further experiments are planned which are yet to be conducted.

2. Experimental Facility

Figure 1 shows the schematic of the experimental facility used for the test. The steam generator (SG) vessel was designed by scale-down model of actual steam generator in Korean nuclear power plants, except the separator and dryer section. Different kinds of tubes, short single tube, short tube bundle and U tube bundle, are prepared for the test, however, only single tube results are shown in this paper.

To simulate the insoluble radioactive aerosol, SiO_2 particles with mass mean diameter (MMD) of 0.7 μm were used. The measured standard deviation was 0.14 μm. The SiO_2 particles were dispersed in ethanol with 20% wt., and the ejected into the mixing chamber with hot carrier gas. Then the ethanol evaporates in the mixing chamber and the SiO2 particles are dispersed in the hot carrier gas, which form aerosols.

The sampling systems were attached at the test facility to measure the aerosol concentration at several positions. The sampling system measures the aerosol mass using the glass fiber filter and the electrical low pressure impactor (ELPI, DEKATI). The gas mass flow through the filter were measured using mass flow controller (MFC, Line Tech or Bronkhorst). Then, the aerosol concentration were calculated with the aerosol mass collected in the filter and the measured gas volume. ELPI measures the aerosol number of mass with respect to the size, by using multiple impactor stages.

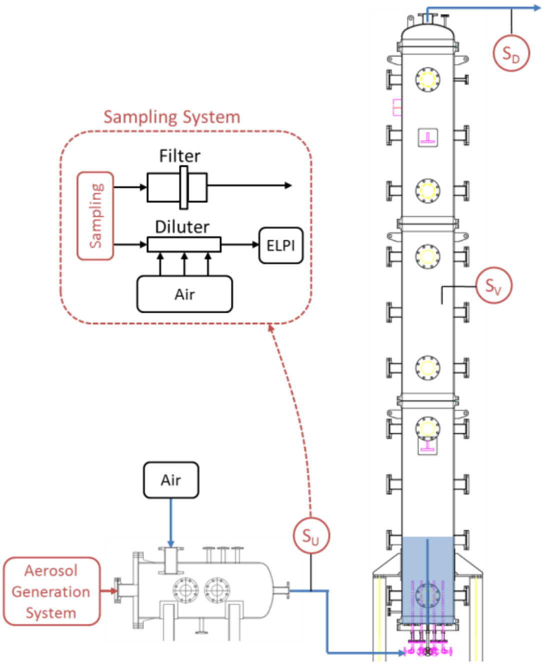

Fig. 1 Schematic of Experimental Facility

3. Experimental Condition

Table 1 shows the thermal-hydraulic condition of the dry and the flooded experiments. The carrier gas were air instead of steam to neglect the aerosol removal by the condensation. The pressure at the primary side, which is upstream of the tube were 6.0 bar in the dry experiment and 6.5 bar in the flooded experiment. In both condition, the flow were in choked condition. The downstream behind the tube were in low pressure condition, about 1.3 to 1.4 bar. The mass flow rate of the air were 0.19 to 0.20 kg/s and the gas temperature at the upstream were about 170°C. The supplied air were heated by the steam heater and the wall of the vessel and the pipes are electrically heated and insulated. The downstream temperature were set to be the same as the upstream temperature, however, the temperature becomes lower in the flooded experiment because of the water temperature in the vessel, which is 50 °C.

Figure 2 shows the tubes used for the experiments. The right tube in the figure were used in the dry experiment, which ejects air upward. Since the flow at the tube is in choked condition, the pressure varies along the tube. Therefore, two pressure taps were made along the tube to measure the pressure during the experiment.

Table 1 Parameters affecting design limit CHFR

Variabe	Dry	Flooded
Working fluid	Air	
Upstream pressure (bar)	6.0	6.5
Downstream pressure (bar)	1.4	1.3
Gas temperature (°C)	170	170
Mass flow rate (kg/s)	0.20	0.19
Water level in vessel (m)	0	1.0
Water temperature (°C)	-	50

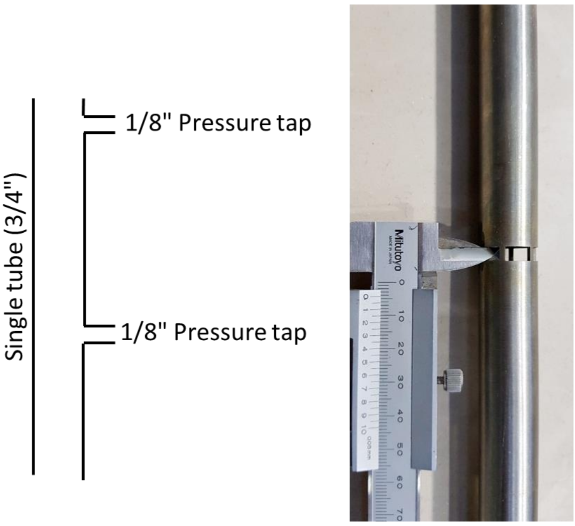

Fig. 2 Tubes used for dry (left) and flooded (right) test

On the other hand, the tube used in the flooded experiment has circumferential opening whereas the tube used in dry experiment opens upward, because the violent upward jet can penetrate the pool in the SG, removing the pool scrubbing effect in the vessel. The circumferential opening were made to have the same opening area as the cross section area of the tube, resulting in the similar velocity at the tube exit. The Weber number at the exit was calculated to be 9.8e6.

4. Experimental Results

Table 1 and 2 shows the decontamination factor calculated from the collected air volume and aerosol mass during the experiments. The aerosol were sampled at the outlet of the mixing chamber (upstream) and at the outlet of the SG vessel (downstream) to estimate the aerosol removal in the SG vessel.

Table 1 Decontamination factor of dry experiment

Variabe	Upstream	Downstream
Sampling time (s)	600	2400
Flow rate (lpm)	3.8	5.9
Volume of air (m^3)	0.038	0.236
Aerosol mass (mg)	225.3	73.3
Raw density(mg/m^3)	5867.5	309.7
Concentration ratio	1.135	1.262
Correct. Density (mg/m^3)	5170.3	245.3
Decontamination factor	21.1	

Table 2 Decontamination factor of flooded experiment

Variabe	Upstream	Downstream
Sampling time (s)	600	2400
Flow rate (lpm)	3.8	5.9
Volume of air (m^3)	0.038	0.236
Aerosol mass (mg)	225.3	73.3
Raw density(mg/m^3)	7836.1	40.5
Concentration ratio	1.127	1.218
Correct. Density (mg/m^3)	6954.0	33.3
Decontamination factor	208.8	

The sampling volume rate at the sampling systems were not in isokinetic condition due to the practical limit of the inhalable capacity, causing the error in aerosol concentration during measurement. However, the non-isokinetic sampling can be compensated using the Stokes number and the velocity ratio as

$$\frac{C}{C_0}=1+\left(\frac{U_0}{U}-1\right)\left(1-\frac{1}{1+(2+0.62U/U_0)Stk}\right)$$

where C and C_0 are the concentration with the actual and the isokinetic condition, U and U_0 are the velocity of the actual and the isokinetic one, and Stk is the Stoke’s number defined for the sampling nozzle diameter and U_0.

Then, the overall decontamination factor considering the concentration ratio were 21.1 for the dry experiment and 208.8 for the flooded experiment, which shows about 10 times of difference by the pool scrubbing effect.

Figure 3 and 4 shows the aerosol mass distribution at the upstream and the downstream during the dry experiment. The upstream shows the clear increase of aerosol mass in most of aerosol size. The downstream shows overall increase of aerosol, however, the mass values at all size region are significantly smaller than those at upstream.

Figure 5 and 6 shows the aerosol mass distribution at the upstream and the downstream during the flooded experiment. In downstream, the aerosol mass showed almost no increase or even decreased during aerosol generation, because the aerosol concentration at downstream were too low to be measured using ELPI device. This non-measurable issue can be solved by re-designing the diluter in front of the ELPI.

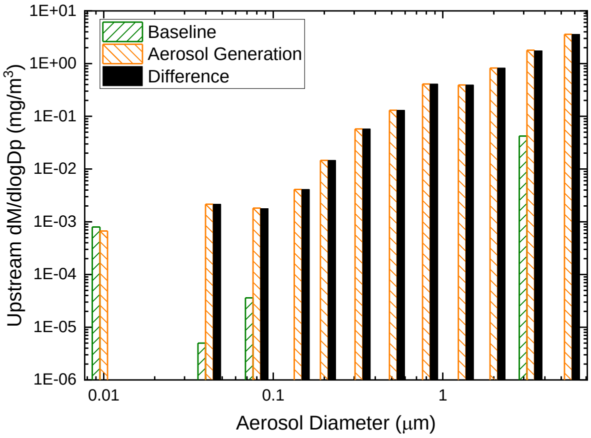

Fig. 3 Aerosol mass distribution at upstream during dry experiment

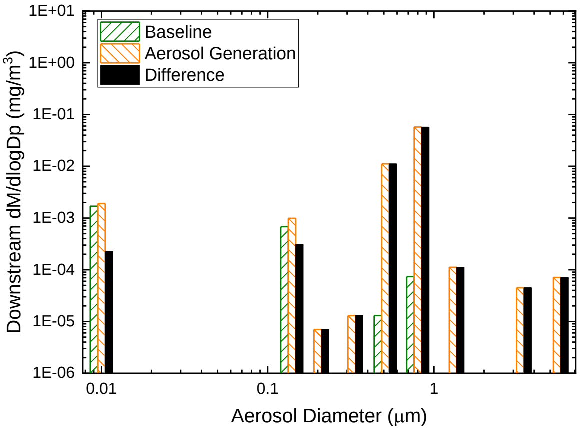

Fig. 4 Aerosol mass distribution at downstream during dry experiment

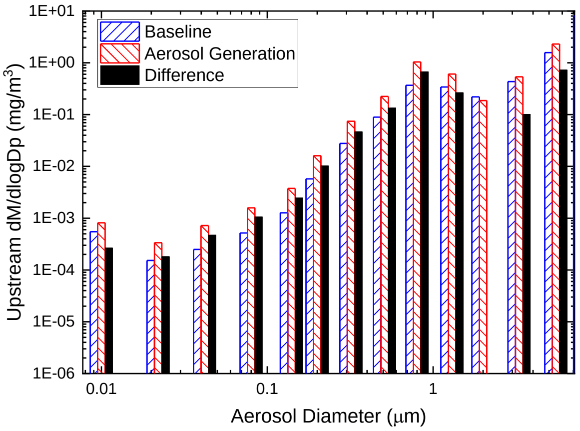

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Fig. 5 Aerosol mass distribution at downstream during flooded experiment

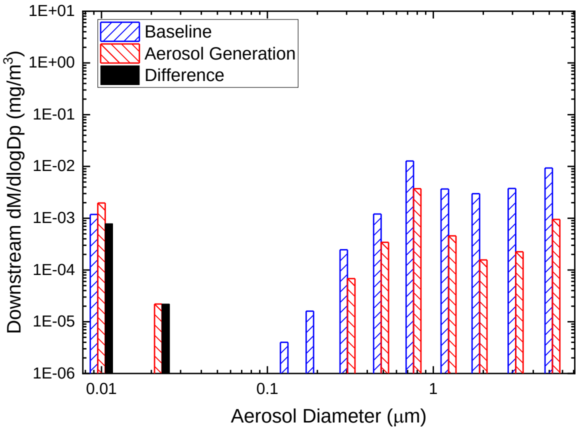

Fig. 6 Aerosol mass distribution at downstream during flooded experiment

5. Conclusion

The aerosol removal in steam generator were examined experimentally using scaled-down SGTR experimental facility. The SiO2 particle of MMD = 0.7μm were used to generate aerosol with hot air as the carrier gas. The single tube was installed in the SG vessel, and the aerosol with carrier gas was ejected through the tube and passes through the vessel. The decontamination factor in the SG were calculated from the ratio of the aerosol concentration at the upstream and the downstream of the facility. The decontamination factor with dry SG were 21.1 and that with flooded SG were 208.8, which shows about 10 times larger aerosol removal by the pool scrubbing. The aerosol size distribution were measured using ELPI, however, almost no aerosol were collected because of the low aerosol concentration in flooded experiment.

More experiments including the experiment using tube bundle are planned or in progress, and the results will be discussed further.

Acknowledgement

This work was supported by the Korea Institute of Energy Technology Evaluation and Planning (KETEP) grant funded by the Korea government (Ministry of Trade, Industry and Energy) (No.KETEP-20171510101970) and the National Research Foundation of Korea (NRF) grant funded by the Korea government (Ministry of Science, ICT, and Future Planning) (No.NRF-2017M2A8A4015280)

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