Pool Scrubbing Characteristics under Horizontal Gas Injection

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1. Introduction

The transport behavior and filtration efficiency of aerosols through stagnant water pool can be important phenomena to estimate the amount of radioactive materials, which can be released into the environment during severe accidents. This is because several severe accident scenarios consider the pool scrubbing phenomenon as a removal mechanism for reducing the amount of the radioactive particles which can be released into the environment.

Pool scrubbing phenomenon represents that aerosols are scrubbed when a gaseous stream is discharged into a liquid pool. Several aerosol removal mechanisms including bubble dynamics occur near the injection region and during the bubble rise towards the liquid surface [1]. Schematic of pool scrubbing mechanism is shown in Fig 1.

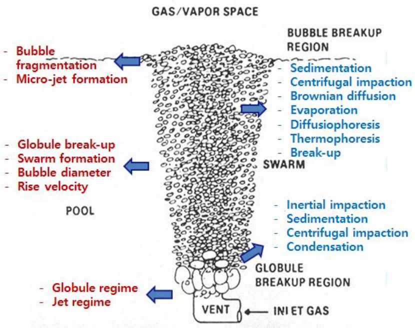

Fig 1. Schematic of pool scrubbing mechanisms [2]

The flow characteristics near the injector can be defined as globule or jet regime depending upon the Weber Number determined by Equation (1).

$$\mathrm{We} = \frac{\rho_l v_g^2 d_{in}}{\sigma} \tag{1}$$

where ρ_l is the liquid density in the pool, v_g is the gas velocity, d_{in} is the nozzle diameter and σ is the surface tension of the liquid. The jet flow regime is determined when the weber number is greater than 10^5. Otherwise, it is globule regime [3]. The schematic of flow regime near the injection regime is shown in Fig 2.

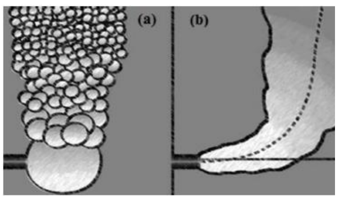

Fig 2. Schematic of flow regime near the injection region: (a) globule regime (b) jet regime [4]

Some pool scrubbing codes consider the aerosol removal mechanism such as impaction, sedimentation, Brownian diffusion, evaporation, and condensation applied in the injection region. On the other side, impaction, sedimentation, Brownian diffusion, evaporation, diffusiophoresis and bubble break-up effects are demonstrated in the bubble rise zone and the liquid surface [5]. The effects of these mechanisms are estimated by the test conditions including whether the bubbly rise zone exists or not. The amount of aerosol removal can be evaluated by the decontamination factor (DF) shown as Equation (2).

$$\mathrm{DF} = \frac{\dot{m}_{in}}{\dot{m}_{out}} = \frac{1}{1-\eta} \tag{2}$$

where η is the particle collection efficiency $(\eta = \dot{m}_{ref}/\dot{m}_{in})$, $\dot{m}_{ref} = \dot{m}_{in} - \dot{m}_{out}$.

There were several existing studies conducted on pool scrubbing which can observe various parameters affected on the scrubbing efficiency such as aerosol size, steam fraction of the main carrier gas, injector submergence, and the Weber number.

The primary purpose of this study was to obtain the experimental database on the aerosol pool scrubbing phenomenon under the condition of the Weber number from globule and jet regime with the consideration of the vital parameters

2. Experimental set up and test conditions

The experimental facility consisted of three components: a thermal-hydraulic supply system, aerosol related systems such as aerosol generator and aerosol sampling system, and a pool (test section) which was a cylindrical vessel with 1200mm diameter and 3800mm height. The thermal-hydraulic system supplies aerosol carrier gas such as steam and air with controlling pressure, temperature and flow rate of the system. The aerosol generator used a two-fluid nozzle to generate and inject aerosol into the system from a mixture of silicon dioxide (SiO_2) with ethanol. In addition, there were two sampling systems to measure the aerosol concentration at the inlet and the outlet of the pool. During the aerosol sampling, aerosols were flew in the carrier gas through a sampling probe inside a pipe and the sampling flow rate was controlled by a Mass Flow Controller and an orifice when the carrier gas was non-condensable gas or steam mixture, respectively. The pool, i.e. the test section had six windows for observing inside the pool in terms of pool elevation and flow direction shown as Fig 3. In addition, to inject the carrier gas with aerosols into the pool, a simple conical shape of the nozzles with 5 and 12mm diameter were suggested for this study shown in Fig 4. The injection nozzle was submerged inside the water pool during the experiments.

The thermal-hydraulic condition of the tests such as pressure, flow rate of the main carrier gas and temperature was regulated by several values, the injecting nozzle and pre-heaters.

The pressure and the main carrier gas flow rate of each test condition had a dependency with the area of the flow path. Thus, valve opening area was controlled to satisfy the each test conditions. The main carrier gas for the tests was heated and maintained about 50℃ before mixing with the aerosols and its carrier gas leading to evaporation of ethanol used for injecting the aerosols into the test section. As a result, the temperature of the main carrier gas was controlled about 20~30℃ at the inlet of the submerged nozzle. In addition, the temperature of the pool was set about 30℃ for the test conditions using non-condensable gas as a main carrier gas and the steam saturation temperature was established for the tests under steam mixture condition.

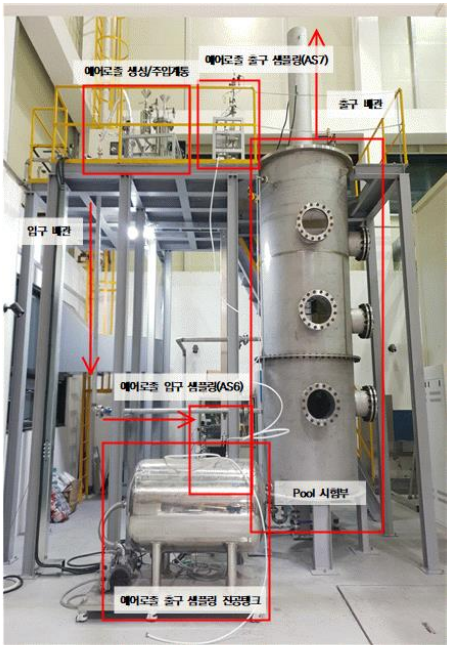

Fig 3. Picture of aerosol pool scrubbing facility

(a) 12mm nozzle

(b) 5mm nozzle

(c) Horizontal injection nozzle

(d) Vertical orientation of injection nozzle

Fig 4. Configuration of injection nozzle

The test conditions of this study was established with respect to the vital parameters such as nozzle submergence, the Weber number, steam faction of the main carrier gas, the injector size, aerosol size, and injector orientation.

Table I: Test Conditions

Target Effect	Case No.(Condition)	Remark
Submergence	JA-03(500mm), JA-03-WL1(1300mm), JA-02(2100mm)	Air, Jet, 0.7μm
We#	GA-03 (7.8×10^4), GA-01 (3.9×10^5) JA-01 (1.2×10^6), JA-03 (1.9×10^6), JA-03(a) (4.0×10^6), JA-04 (6.3×10^6)	Air, WL:500mm, 0.7μm
Stream Fraction	JA-04(0 wt%), JS-03-SF1(40wt%), JS-03(80wt%)	Jet, WL:500mm, 0.7μm
Injector orientation	JA-05(Vertical), JA-07(Horizontal)	Air, Jet, WL:500mm, 0.7μm
Aerosol Size	JA-04-AS1(0.3μm), JA-04(0.7μm), JA-04-AS2(1.5μm)	Air, Jet, WL:500mm

3. Test Results and Discussion

There were fifteen test conditions which were conducted for this study. The effects of the target variables on the aerosol removal efficiency during pool scrubbing were compared under the similar thermal-hydraulic conditions in order to verify the correlation between the variables and the scrubbing efficiency.

The decontamination factors of each test conditions were calculated by using the aerosol concentrations at the inlet and the outlet of the test section. These aerosol concentrations were converted using the aerosol sampled masses and the sampled flow rate obtained from the aerosol sampling systems. When the every test was conducted, the aerosol sampling was performed for 6 times at the inlet and 3 times at the outlet with the period of 5 min. and 20 min., respectively. The reason why the sampling period was different is because the expected aerosol concentration at the inlet was much higher than the one at the outlet. However, in order to get the simultaneous aerosol concentration, the inlet aerosol sampling was conducted during the first and the last 5 min. of the outlet sampling period. In addition, the aerosol concentrations of each test were averaged in order to get the representative decontamination factor.

The relationship between the nozzle submergence and the DF was shown in Fig 5. Three test conditions were conducted under the similar thermal-hydraulic condition. The mass flow rate at the nozzle was about 0.02kg/s converted to the Weber number of about 2.0×10^6 defined as the jet regime and the water temperature in the pool was about 30℃. The main carrier gas was the compressed air with nitrogen gas as aerosol carrier gas and the nozzle had 12mm diameter.

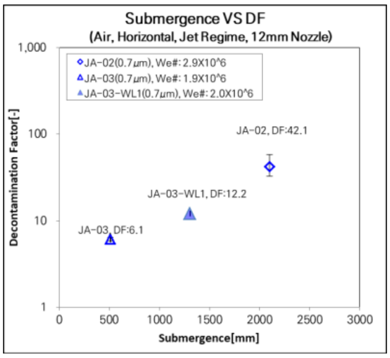

Fig 5. DF with the nozzle submergence difference (horizontal injection, 12mm nozzle)

The pool scrubbing efficiencies in Fig. 5 were 83.7 91.8, and 97.6%, respectively. The differences of the pool scrubbing efficiency among the test cases were about 8% of each interval of the submergence.

The effects of the Weber number on aerosol pool scrubbing can be observed in Fig. 6. Six tests were conducted under the similar thermal-hydraulic conditions such as using non-condensable gas as a main and aerosol carrier gas with about 500mm nozzle submergence which can be expected to remove the effect of the bubble rise zone. The gas was injected into the pool having a temperature of 30℃ parallel to the floor of the pool.

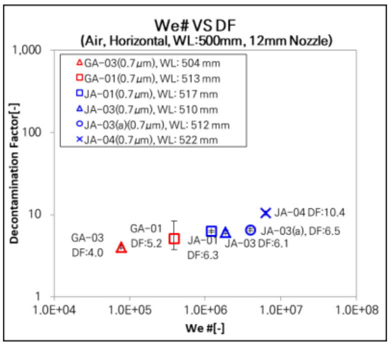

Fig 6. DF with Weber number (WL:500mm, horizontal injection, 12mm nozzle)

As shown in Fig. 6 the DF increased with an increase in the Weber number, which indicated the effect of impaction by inertia near the injection zone on the pool scrubbing increased with the injection flow rate. The DF increased from 4.0 to 10.4 with an increase in the Weber number from 7.8×10^4 to 6.3×10^6. The Weber number of 10^5 can be a border to decide whether the flow regime is jet or globule regime [4]. Therefore, it can be inferred that the pool scrubbing effect was stronger in the jet regime than the globule regime.

Although the trend of the DF changes in terms of the Weber number in this study was matched with the one from the previous studies, the amount of the DF changes varied with the one from the previous studies. Some of them have similar increasing trend with this study. Others were different from this study. For example, the experimental results obtained from the POSEIDON II [4-9], which had similar condition with this study, the DF was smaller than the one for this study, even though they were under the higher Weber number condition. In this study, the test results shown in Fig. 6 were measured under the minimum nozzle submergence condition. This condition can remove the most of the effects caused by the nozzle submergence. Thus, the effect of the Weber number on the DF was less significant compared to the one caused by the nozzle submergence.

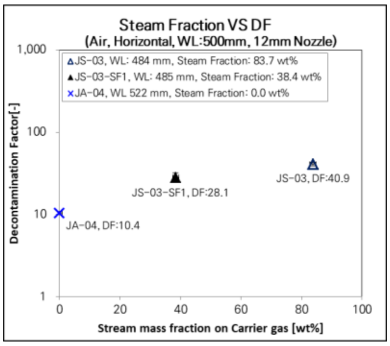

Fig 7. DF with the nozzle submergence difference (horizontal injection, 12mm nozzle)

The effect of the steam fraction of the main carrier gas on the DF was examined and the results were presented in Fig. 7. Three test cases were conducted under the similar thermal-hydraulic conditions except the steam fraction of the main carrier gas which was 0wt%, 40wt% and 80wt%, respectively. The carrier gas was injected into the pool toward parallel to the floor of the pool using the 12mm nozzle with 500mm nozzle submergence.

As shown in Fig. 7, the DF increased with the increase of the steam fraction of the main carrier gas. In addition, the nozzle submergence was expected to show only the region of the injection zone rather than the bubble rise zone. Therefore, it was inferred that the steam condensation inside the water of the pool affected the pool scrubbing efficiency.

In addition, the effect of the aerosol size on the pool scrubbing efficiency was investigated under the similar thermal-hydraulic test conditions except the size of the aerosols. The nozzle submergence of the test conditions was about 500mm with the Weber number of roughly 5.5×10^6. Fig 8 shows that the results of the test condition of using the aerosol particles having 0.3, 0.7, 1.5μm diameter, respectively. In addition, the aerosol used in this study was silicon dioxide which had spherical shape that can be expected that the shape effect on the DF was removed. Therefore, the results can be inferred that the pool scrubbing efficiency increased with increase of aerosol particle size.

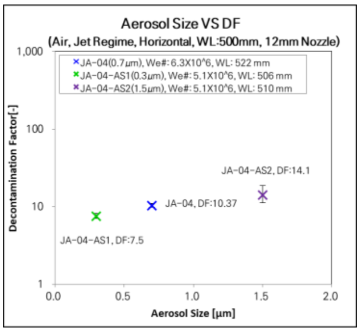

Fig 8. DF with the aerosol particle size difference (horizontal injection, 12mm nozzle)

The direction of the flow injection into the pool was examined by the two test conditions. The test conditions considered two direction of the injection such as parallel and vertically perpendicular to the floor of the pool under the similar thermal-hydraulic conditions such as using non-condensable gas for the main carrier gas, the Weber number of 2.7×10^6 with 500mm nozzle submergence and the pool temperature of 30℃.

Although the removal of the effect on the bubble rise zone, the bubble path toward the water surface between two test conditions were different from each other. The horizontal injection was able to have longer path than the vertical injection which means the pool scrubbing efficiency of the horizontal injection can be higher than the one from the vertical injection. This can be confirmed by the results shown in Fig. 9. The difference of the pool scrubbing efficiency between two tests was about 2%.

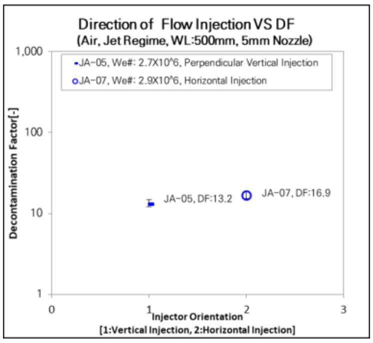

Fig 9. DF with the different injector orientation (jet regime, 5 mm nozzle)

4. Conclusion

In this study, the aerosol retention performance for the pool scrubbing phenomena was experimentally investigated under various test conditions. The quantitative DF of sub-micron SiO_2 particles were obtained based on the test parameters such as the Weber number, nozzle submergence, steam faction of main carrier gas, aerosol particle size and flow direction of the injection through submerged nozzle. Table II summarizes the pool scrubbing behavior in terms of the test parameters obtained from previous experiments and this study. The test results in this study explain that if the parameters in Table II increases, the pool scrubbing efficiency for tiny aerosol particles will be increased. Also, the results from the previous experiments are well agreed with the one from this study.

Table II: Pool scrubbing behavior with test parameters

Research	Aerosol size	Steam fraction	Submergence	We# (flow)	DF
UKEA (1996)[5]	-	∞ DF	-	-	-
GE (1982)[5]	∞ DF	-	∞ DF	∞ DF	7~2900
EPRI (1991)[5]	∞ DF	-	∞ DF	-	1.4~5600
JAERI (1987)[5]	-	-	∞ DF	∞ DF	1.5~40
ACE (1992)[5, 6]	-	-	∞ DF	∞ DF	11~2600
LACE (1992) [5, 6]	∞ 1/DF	-	-	∞ DF	16~2913
RCA (1996) [4, 6, 7]	-	-	∞ DF	-	12.4~1220.7
POSEIDON-II(1998) [4, 6, 7, 8, 9]	-	-	∞ DF	∞ DF	3.4~39.8
ARTIST-II (2011) [4, 8, 10]	∞ DF		∞ DF	∞ DF	53~2780
PSP (2018)[4]				∞ DF	14.1~294.1
This study	∞ DF	∞ DF	∞ DF	∞ DF	4.0~42.1

It is expected that results obtained from this study will be used as benchmark data to develop the aerosol retention models for pool scrubbing phenomena, and these data will be a basis to develop the strategy to handle to release radioactive aerosols into the environment during postulated accidents in a nuclear power plant. In the future, additional experiments could be necessary for covering wider range in terms of test parameters.

5. Acknowledgements

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References

[1] W.Y. Jung, D. Lee, J. Kang, M. Ko, B.K. Kim, J. C. Lee, , D.Y. Lee, B. and Lee, K. S. Ha, Experimental study of pool scrubbing under horizontal gas injection, Annals of Nuclear Energy, Vol. 171, 109014, 2022.

[2] P. Owczarski, and K. Burk, SPARC-90: a code for calculating fission product capture in suppression pools, U.S. Nuclear Regulatory Commission, 1991

[3] D. Paul, J. Flanigan, A. Cudnik, C. Cunnane, P. Collier, and N. Oehlberg, Radionuclide scrubbing in water pools, s.1.: Electric Power Research Institute, 1985

[4] L. Herranz, R. Iglesias, and J. Fontanet, Mitigation of source term in suppression pools: Large uncertainties in predictability, Annals of Nuclear Energy, Vol. 120, pp. 509-515, 2018

[5] E. Berzal, J. Crespo, M. Swiderska-Kowaiczyk, M. Espigares, and L. Jimenez, State-of-art review on fission products aerosol pool scrubbing under severe accident condition, s.1.; European Commission, 1995

[6] C. Berna, A. Escriva, J. Muñoz-Cobo, and L. Herranz, Enhancement of the SPARC90 code to pool scrubbing events under jet inejction regime, Nuclear Engineering Design,Vol.300, pp.563-577, 2016

[7] C. Berna, A. Escriva, J. Muñoz-Cobo, and L. Herranz, Study of pool scrubbing events under jet injection regime, conference proceeding, 12th international conference on Heat Transfor, Fluid Mechanics and Thermodynamics, 2016

[8] A. Dehbi, D. Suckow, and S. Guentay, Aerosol retention in low-subcooling pools under realistic accident conditions, Nuclear Engineering and Design, Vol.203, pp.299-241, 2001

[9] A. Rýdl , L. Fernandez-Moguel, and T. Lind, Modeling of aerosol fission product scrubbing in experiments and in integral severe accident scenarios, Nuclear Technology, Vol.205(5), pp.655-670, 2018

[10] T. Lind, A. Dehbi, S. Guntay, Aerosol retention in the flooded steam generator bundle during SGTR, Nuclear Engineering and Design, Vol.241, pp.357-365, 2011