Effects of the Baffle Plate of the Advanced Venturi Scrubber

on Decontamination Factor of the Filtered Containment Venting System

**Abstract** After the accident at the Fukushima nuclear power plant, filtered containment venting systems (FCVSs) have garnered increasing attention as an effective facility for nuclear accident management. FCVSs with a wet-type scrubber, a droplet separator, and several other stages for fine aerosol filtration are typical used of many countries. Most of these FCVSs comprise a self-priming venturi scrubber nozzle for air injection. An optimized design of the VS (in terms of the throat length, throat size, nozzle diameter, etc.,) may significantly improve the filtration efficiency of the nozzle and wet-scrubber filter. Furthermore, adding a baffle plate on top of the VS also can improve the efficiency of the wet-scrubber filter. In this study, to understand the effects of the baffle plate on the efficiency of the wet-scrubber filter, two VS nozzle configurations were used. The difference between these two configurations is that one of them involved a baffle plate installed above the outlet. The decontamination factors of the wet scrubbers using these two nozzle configurations were measured and compared. The two-phase flow pattern in the pool was observed using a high-speed camera. It is discovered that the baffle plate contributed to increase the efficiency of the wet-pool scrubber. Moreover, the aerated surface exhibits better stabilization when the baffle plate is used.

**Keywords:** Filtered containment venting system (FCVS), Wet-type scrubber, Advanced venturi scrubber, Two-phase flow, Decontamination factor.

1. Introduction

The accident at the Fukushima Daiichi nuclear power plant (NPP) in March 2011 severely affected many people. It released a large amount of radioactive material into the environment. One of the most important lessons learned from the Fukushima Daiichi NPP accident is that accident management systems should be developed. A filtered containment venting system (FCVS) is considered as a system that can enhance the capability to suppress or prevent the occurrence of severe accidents because of reducing the pressure, steam water, and flammable gas in containment vessels [1]. In case of an accident occurs, the FCVS minimizes the release of fission products and radioactive materials into the environment [2]. Furthermore, the FCVS Technology can effectively remove radioactive aerosols arising from the dismantling of facilities and the cutting of core debris.
2. Experimental Setup

2.1 Test Facility

A laboratory-scale test facility for simulated a wet-scrubber-based FCVS was constructed at the Tokyo Institute of Technology. A schematic of the test facility is shown in Fig. 1. The system comprises a wet-pool scrubber combine with a droplet eliminator and a multistage dry-type filter. They are connected in series in the pipeline which has an inner diameter of 50 mm. The multistage dry-type filter comprises a combination of several specific filtration layers for different types of simulated radiation aerosols and gases; these filters include meta fiber filters and high-efficiency particulate air (HEPA) filters for fine aerosol particles removal, and zeolite filters for organic iodine removal. In this study, the dry-type filter was used with an HEPA filter to measure the aerosol mass at the outlet of the wet scrubber.

The full-scale wet-scrubber FCVS had a diameter of approximately 4 m. It was deployed with many venturi nozzles. The wet scrubber used in this study was designed with a scale of 1:20; and only a single VS nozzle was used. The wet scrubber was a
vertical cylindrical pool composed of transparent acrylic with an inner diameter of 20 cm; it had a wall thickness of 1 cm and a total length of 200 cm. The working liquid was water. The VS nozzle was installed at the bottom of the pool to inject the venting gas to the pool.

The simulated air venting flow was supplied by two air blowers (ETG Japan Vacmaster VO1220SFD-SP). The venting flow rate could be adjusted by the control valves on the pipeline downstream of the air blowers. Pressure gauges and a flowmeter were installed to indicate the pressures and flow rate of the air injected flow.

Downstream of the wet scrubber, a metallic zigzag vane mist eliminator was installed to remove entrained water droplets in the airflow before it entered the dry-type filtration layers.

2.2 Air Nozzle

In recent studies, VSs were typically used as the nozzles of the wet-pool scrubbers of FCVSs. VSs are one of the most effective nozzles that can remove dust particles through contact with water droplets in the throat and diffuser of the nozzle [7]. The self-priming VS has been optimized in several studies to improve its radioactive aerosol or gaseous material removal capacity [8, 9]. However, in a wet-type pool scrubber of FCVSs, the VS is usually submerged in the pool water; and the two-phase flow behavior of the pool significantly affects the efficiency of the FCVSs [10]. Therefore, adding a baffle plate at the exit of the nozzle to change the gas flow behavior should contribute positively toward the decontamination factor (DF) of the wet scrubber.

VS nozzles are typically designed with cylindrical or rectangular cross-sections; both are used in the actual design of the wet scrubbers in FCVSs for NPPs [11]. In this study, a self-priming VS nozzle with a rectangular cross-section was used for bubble generation. The advantage of this type of venturi nozzle is that it is a two-dimensional nozzle, therefore its similarities with actual FCVS nozzles can be scaled up easily by adjusting the nozzle depth. Additionally, the two-dimensional nozzle allows the two-phase flow behavior to be observed easily. The nozzle was developed by Fujii et al. [12], is known as advanced venturi scrubber (AVS) nozzle. Fig. 2 depicts the design (a) and actual image of the AVS (b). It was designed as a double-stage VS with a throat size of 14 mm × 58 mm and the maximum cross-section of the diffuser (the exit) was 60 mm (width) × 58 mm (depth). The total height of the nozzle was 290 mm. At the exit of the AVS, a baffle plate was installed to change the gas flow direction from vertical to lateral and increase the turbulent flow in the pool. To understand the effect of this baffle plate on the aerosol removal efficiency and the flow behavior of the wet-pool scrubber, experiments were conducted for two configurations of the AVS: with and without the baffle plate.

2.3 Visualization Measurement system

The flow pattern in the scrubbing pool of the wet-type filter was visualized using a high-speed camera (Photron Fastcam Mini AX50) with the Nikon 60mm f/2.8G lens. Fig. 3 shows a schematic of the
3. Decontamination Factor Measurement

The aerosol removal efficiency of the wet-type scrubber was tested using BaSO4 powder (BARIACE B-54, Sakai Chemical Industry Co., Ltd.) as the simulated aerosol particles. The diameter distributions of several types of powder were measured by Narabayashi et al. [4]; these are depicted in Fig. 5. The diameter distribution of BaSO4 powder was similar to that of aerosol particles in the event of a severe nuclear accident.

The efficiency of the filter is represented by the DF, which is defined as the ratio of the aerosol concentrations at the inlet and outlet of the filter. Given that the air venting flowrate remained constant for each measurement, the DF can be estimated as the ratio of the mass of aerosol fed at the inlet ($M_{in}$) to the mass of aerosol collected at the outlet ($M_{out}$) of the filter:

$$DF = \frac{M_{in}}{M_{out}}$$

The DF was measured as follows. First, BaSO4 powder was dried in order to break any lumps in the powder; it was then exposed to air to attain the indoor humidity. The BaSO4 powder was then weighed and placed in the aerosol feeder. Thereafter, the filtered system was turn on; after adjusting the required parameters and ensuring that the system operated in a stable manner, the valve on the aerosol feeder was opened to feed aerosol powder to the venting flow. The system was operated until the BaSO4 powder in the aerosol feeder was completely depleted. Subsequently, the mass of aerosol particles collected at the outlet was determined.

To collect the aerosol powder at the outlet of the filter, a HEPA filter (DCC1009, DENSO Corporation) was used at the dry-type filter stage. For each measurement, two layers of the DCC1009 HEPA filter supported by a metal punching plate (as shown in Fig. 6) were installed downstream of the diffuser (as shown in Fig. 1). The HEPA filters were dried and exposed to air for about 12 hours to attain the indoor humidity before they were weighing. The net mass of aerosol powder collected by the HEPA filter was determined by subtracting the weight of the fresh HEPA filter from the weight of the HEPA filter after the experiment. The DF of the wet scrubber was calculated using Eq. (1).
4. Results and Discussion

4.1 Flow Visualization

To understand the effects of the baffle plate on the flow pattern, the flows at the upper portion and the exit of the nozzle were observed. Fig. 7 shows the flow patterns obtained by using the high-speed camera for both configurations of the AVS: with and without the baffle plate. At high flow rate of the injected air i.e., at full capacity of the air blowers (as shown in Figs. 7c), and 7d), the density of bubbles in the pool was extremely high. The overlapping of numerous bubbles reduced the visibility of the patterns captured via the camera. However, a similar flow behavior was observed more clearly at a lower flow rate of the injected air (as shown in Figs. 7a) and 7b)).

The motions in the gas phase for two cases were different. Without the baffle plate, the bubbles escaped from the AVS nozzle and continued to accelerate under the buoyancy force which acted in the same direction as the bubble velocity. In the case of using AVS with the baffle plate, the bubbles moved downward. Under the effect of the buoyancy force, the bubbles initially decelerated and then reached zero velocity at a location below the exit of the nozzle. Subsequently, they were accelerated and moved upward. Therefore, the baffle plate decreased the rising of bubbles; in other words, it increased the residence time of the bubbles in the pool. It is noteworthy that a longer residence time implies a higher probability that the particles inside the bubble come in contact with the gas liquid surface [13]; This would lead to an improvement in the DF.

In general, the motion of aerosol particles in an airflow is affected by Brownian diffusion, gravitational force, and inertial sedimentation [14]. Brownian diffusion is strongly dependent on the properties of the fluid, such as viscosity and temperature. However, inertial forces are affected by the movement of the bubbles. As the specific density of the particles is considerably higher than that of air, a change in the direction of airflow due to the contact with the baffle plate may significantly affect the inertial sedimentation of aerosol particles. The mechanism of the increase of decontamination factor due to interaction of particles with the baffle plate can be explained as description in Fig. 8. It is noted that in performance of venturi scrubber nozzle, the water in atomized into nozzle though a small gap on the throat because of difference in static pressure of high velocity gas stream in the throat and hydrostatic pressure of liquid in the tank. By the high velocity of the air stream, the water was formed as small droplets moving with the air stream inside the nozzle. By the installation of the baffle plate, the air stream was changing direction at the exit of the nozzle; and the water droplets under

![Flow patterns at the exit of AVS.](image)

![Interaction of water droplets and aerosol particles with the baffle plate.](image)
impaction of centrifugal force were slipped out to the inner surface of the baffle plate and formed a thin water layer on it. The centrifugal force also impacted to aerosol particles due to its higher specific weight than that of the air. As a result, the aerosol particles tended to move to the baffle plate and be absorbed into this water film.

4.2 Aerated Water Column Height

To estimate the average water level in the pool, a high-speed camera was used to observe the aerated water surface. The recorded images were transformed into binary images. Subsequently, boundaries of the surface were determined via the image processing. In each recorded frame (such as for the \( i^{th} \) frame), the water levels (\( h_{11}, h_{12} \) and \( h_{13} \)) were determined at three horizontal positions (\( x_1, x_2 \) and \( x_3 \), respectively) at the center and near the walls of the pool (as shown in Fig. 9). The average water level was determined using the following equation:

\[
h_{\text{ave}} = \frac{1}{N} \sum_{i=1}^{N} \left( \frac{h_{11} + h_{12} + h_{13}}{3} \right)
\]

where, \( N \) is the number of recorded frames.

Strong oscillation was observed in the two-phase flow of the wet scrubber. Fig. 10 shows the aerated heights of the bubble column at different initial water levels. The error bars were relatively large because of strong fluctuations in the surface of the water column.

The difference in the aerated height for the two nozzle configurations can be attributed to the effect of liquid circulation. It is noteworthy that water was atomized in the VS through gaps on the nozzle throat because of the pressure difference between the hydrostatic pressure of the liquid pool and the pressure of the gas in the nozzle. With the baffle plate, the atomized water circulated in the region below the nozzle exit. Without the baffle plate, the circulation of atomized water may affect to reduce the slip velocity of bubbles, therefore the gas holdup was increased.

The aerated height of the water column is one of the important factors that affect the efficiency of the pool scrubber due to entrainment effects. According to Kataoka and Ishii [15], the degree of entrainment increases with a decrease in height from the water surface to the outlet at the top of the pool. The water contained aerosol particles that were absorbed during the FCVS operation. Therefore, a higher entrainment degree may decrease the DF of the pool scrubber. However, such the entrainment effects are beyond the scope of this study. The entrained droplets were removed using a zigzag vane mist separator.

4.3 Decontamination Factor

To measure the DF of the wet-pool scrubber, BaSO₄ powder was loaded in the aerosol feeder. The experimental procedure is described in Section 3. To mitigate the deposition of aerosol particles in the pipeline upstream of the nozzle, a high flow rate of air was employed. The highest flow rate obtained at the full capacity of the air blowers was used. The duration for each experiment was approximately 1 h. Thus, the average concentration of aerosol particles at the inlet of the wet-pool scrubber was 3.4 - 4.0 g/m³.

The experimental conditions for the measuring
the DF are showing in Table 1. Nine test cases were conducted for both configurations of the AVS: with and without the baffle plate. Test cases A1: A4 were conducted using the AVS without the baffle plate, whereas test cases B1: B5 involve the AVS with the baffle plate. The aerosol DF of the wet-type filter was measured for different conditions of the initial water level from the bottom of the scrubbing pool. For the cases without the baffle plate, experiments were not conducted at the initial water level of 80 cm because of the strong fluctuations in the free air water surface in the pool. Occasionally, the bulk of water attached to the upper wall and the outlet of the pool, which resulted in inaccurate measurements due to the large amount of water appearing over the mist separator. This may also occur in the AVS with the baffle plate at an initial water level exceeding 80 cm.

Fig. 11 shows a HEPA filter after it was used in the experiment (test case: A1). BaSO₄ powder was trapped in the HEPA filters, forming patches on the green filter. The net mass of aerosols collected by the filter was calculated by subtracting the weight of the fresh HEPA filter prior to the test from the weight of the filter after the test. Subsequently, the DFs was estimated using Eq. (1). The quantitative masses of aerosol loaded at the inlet and collected by the HEPA filter during the experiments are shown in Table 1.

Fig. 12 depicts a comparison of the measured DFs for the wet-type scrubber under the two configurations of the AVS. The DF of the filter increased with the pool depth. This can be explained by the increase in the residence time of air bubbles in water, which, in turn, increased the probability that the aerosol particles inside the bubbles came in contact with the air-water interface of the bubbles.

These measured DFs included the contribution of the mist separator efficiency and disregarded a small amount of aerosol particles deposited on the walls of the system. Additionally, the efficiency of the HEPA filter was not included in the calculation. However, the AVS configurations and the initial water level of the pool were the primary causes of the differences in the DFs.

The DFs of the two AVS configurations were different. The results confirmed that the baffle plate resulted in an increase in the DF of the wet-pool scrubber. As described in Section 4.1, this increase in DF is attributed to the decelerated rising of air bubbles in the pool and the impact of the centrifugal force to aerosol particles at the exit of nozzle.

4.4 Comparison with Previous Studies

The DFs at different submergence depths of the nozzle have been measured in many previous studies. Narabayashi, T. et al. [16] reported that the DF depended on the water pool depth and aerosol particle size, as shown in Fig. 13. In their study, a water stream was injected directly through a large downward pipe (15 cm of diameter). The DF of a full-height scale apparatus determined experimentally and analytically. Their results showed that the DF increased with the water scrubbing pool depth.

Compared to this previous study (Fig. 13), in this study, it was found that the efficiency of the wet-pool scrubber improved substantially when using a
The DF are showing in Table 1. Nine test cases were conducted for both configurations of the AVS: with and without... 55 60 65 70 75 80

Initial Water level [cm]
500
1000
1500
2000
2500

Decontamination Factor
with BP
without BP

| Cases | AVS configuration | Initial Water Level (cm) | Air Injection Flowrate (m³/h) | Aerosol mass fed at inlet (g) | Aerosol mass collected at outlet (g) | DF |
|-------|-------------------|--------------------------|-----------------------------|-------------------------------|------------------------------------|-----|
| A1    | Without BF        | 40                       | 154                         | 535.188                       | 0.931                              | 0.57 E+2 |
| A2    | Without BF        | 50                       | 148                         | 515.064                       | 0.707                              | 0.73 E+2 |
| A3    | Without BF        | 60                       | 139                         | 527.591                       | 0.542                              | 0.97 E+2 |
| A4    | Without BF        | 70                       | 134                         | 523.487                       | 0.405                              | 1.29 E+3 |
| B1    | With BF           | 40                       | 152                         | 524.590                       | 0.444                              | 1.18 E+3 |
| B2    | With BF           | 50                       | 145                         | 520.474                       | 0.372                              | 1.40 E+3 |
| B3    | With BF           | 60                       | 138                         | 521.187                       | 0.322                              | 1.62 E+3 |
| B4    | With BF           | 70                       | 131                         | 468.899                       | 0.264                              | 1.78 E+3 |
| B5    | With BF           | 80                       | 129                         | 495.146                       | 0.217                              | 2.28 E+3 |

It should be noted that a mist separator was not used in Ref. [16], owing to which, entrained droplets in the airflow may a little bit decreased the efficiency of the system. However, it can be neglected due to the entrainment factor is usually small [18]. In this study, the zigzag vane type mist separator was used with the drainage traps. This type of mist separator was effective only for the removal of entrained droplets. Almost aerosol particles that were trapped by the mist separator were already absorbed in the water phase due to pool scrubbing. Based on Kataoka and Ishii correlation [15], the maximum mass of aerosol particles that can be collected at the top of the pool is 0.244 g. This value is calculated as assumption that the experiment was performed in one hour, and the fresh water was used at beginning of experiment.

5. Conclusion

Experiments were conducted to compare the efficiencies of a wet-type pool scrubber under two configurations of the AVS nozzle: with and without a baffle plate installed on the nozzle exit. The conditions at the exit of the nozzle were visualized to understand the effect of the baffle plate on the two-phase flow pattern of the pool. The conclusions can be summarized as follows:

1. Based on the visualization, the baffle plate decreased the velocity of and increased the fluctuations in the bubble motion in the pool by changing its movement direction. Thus, the baffle plate increased the probability of the aerosol particles coming in...
contact with the gas-liquid interface and being absorbed into the liquid phase.
2. When using the AVS with the baffle plate, the aerated water heights were lower. This improved the aerosol removal efficiency owing to reduction in the entrainment rate. Furthermore, the greater pool depth can be maintained than that for an AVS without a baffle plate, leading to an improvement in the efficiency of pool scrubbing.
3. The DFs of the wet-type pool scrubber for different initial pool water levels confirmed that the installation of the baffle plate improved the aerosol removal efficiency of the FCVS.
4. The DF of the wet scrubber using the AVS was showed several hundred times higher that that when using direct downward air injection of a large pipe.

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