湿式エアロゾルフィルターのスクラビングプールにおける二相流の挙動に関する実験およびシミュレーション

Experimental and Simulation Studies on the Two-phase Flow Behavior in the Scrubbing Pool of the Wet-type Aerosol Filter

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For decommissioning of the Fukushima Daiichi Nuclear Power Plant, a high efficiency Filtered Containment Venting System should be equipped to prevent the releasing of radioactive material to environment. The wet-type aerosol filter is the first stage of the Filtered Containment Venting System, and it plays significant role to removal the aerosol particles from the venting system. The decontamination of the filter strongly depends on the two-phase flow pattern in scrubbing pool of the filter. Therefore, in order to improve the efficiency of the filter, the flow behavior should be well understood. In this study, the experiment and simulation were conducted to understand the two-phase flow behavior in the scrubbing pool of the filter due to air flow injection. In experiment, the optical visualization method was used to measure the parameters of bubbles such as bubble size, bubble velocity. In simulation, the two-phase flow analyses were performed using the TRAC-BF1 code.

Keywords: Severe accident, Filtered containment venting system, Wet-type aerosol filter, Scrubbing pool, Two-phase flow, TRAC code.

1. Introduction

Eight year after the accident of the Fukushima Daiichi Nuclear Power Plant on March 2011, the reactors were shown to be heavily damaged with the severe core meltdown and dripping to the bottom of the reactor vessel [1]. Therefore, for decommissioning of the Fukushima Daiichi Nuclear Power Plant, the cutting process to break up the core debris should be required. This process may release a large amount of radioactive gas and aerosols into the reactor vessel. To prevent the release of these radioactive gas and aerosol to the environment and to ensure the working condition of the low levels of radiation in a long time, the high-efficiency air cleaning system should be equipped.

As the requirements on the high efficiency filtered venting system for decommissioning of the Fukushima Daiichi Nuclear Power Plant, an integral filter system has been developed by Prof. Narabayashi. The system consists of several filter layers, such as a wet-type aerosol filter, metal fiber filter (dry-type) and a silver zeolite filter for removal radioactive aerosol particles and organic iodine from the venting system. The filter system seems to success to remove even the nanometer-size aerosol particles with the decontamination factor (DF) for the wet-type and dry-type are 3.460 and 67.506, respectively [2].

The first stage of the system - the wet-type filter play an important role to remove the aerosol particles from the venting system. And the efficiency of the wet-type aerosol filter strongly depends on the behavior of the two-phase flow in the scrubbing pool of the filter. Therefore, understanding on the two-phase flow of the scrubbing pool is important to develop this filter for the economic aerosol filter.

In this study, the optical visualization method using a high-speed camera was conducted to investigate the two-phase flow behavior in the scrubbing pool of the wet-type aerosol filter. The behavior of bubble distribution was evaluated in different condition of the venting flow rate. In order to develop the design of the filter, the computational analysis code should be used. In this paper, the flow behavior was also analysis using TRAC (Transient Reactor Analysis Code) computational code which was developed by the Los Alamos Scientific Laboratory (LASL).

2. Experiments

2.1. Experimental apparatus

Figure 1 shows a simple schematic of the experimental apparatus of the wet-type aerosol filter of the FCVS. The vertical cylindrical scrubbing pool is made of transparent acrylic with the inner diameter of 20 cm, and the total length of 2 m. The air flow was supplied by an air compressor and injected to the filter through a venturi scrubber nozzle at the bottom of the scrubbing pool. The venting flow rate can be adjusted by the controlling valve which installed at the upstream pipeline of the venturi scrubber. The air venting flow rate was determined by the air flowmeter installing after the control valves.

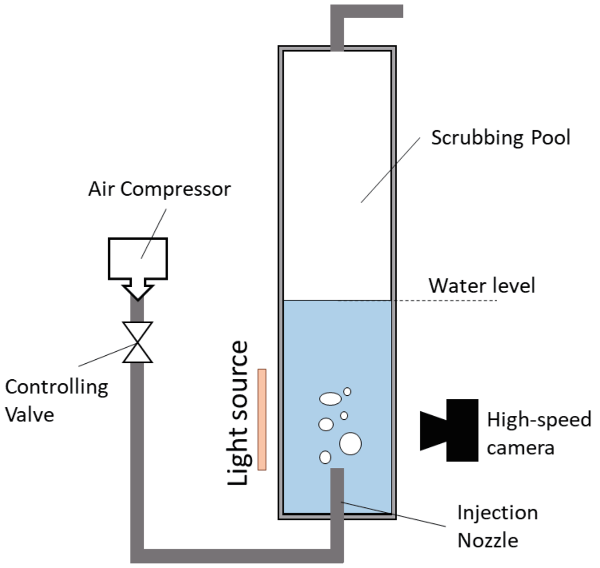


Fig. 1. Simple schematic diagram of the experimental apparatus.

2.2. Visualization measurement

The two-phase flow behaviour in the scrubbing pool was observed using a high-speed camera (Fastcam mini AX50 manufactured by Photron Co. Ltd.) with the Nikon 60mm f/2.8G lens; the backlight was set up on the opposite side of the pool. The aperture of the lens was close to small enough so that all the bubbles in the scrubbing pool at the measurement section can be focused. In order to avoid the refraction of the light by the cylindrical shape of the scrubbing pool, a water box was installed covering the scrubbing pool at test section as shown in Fig. 2. The High-speed camera was set up at the recording rate of 1000 frames per seconds, the shutter speed of 1/5000 second. By the limitation of the camera memory, at the highest resolution of 1024 x 1024 pixels, a total of 5457 continuous frames were recorded. It permitted the measurement time to be around 5.45 seconds.

The recorded images of the High-Speed camera were processed using MATLAB programming software. Figure 3 shows an example of image processing schedule. The foreground images (b) which included the bubbles only were obtained by subtraction of the raw images (a) to the background image. The foreground image after that converted into binary digitalized image (c) and then fill the inner holds of bubbles (d). From these images, the parameters of each bubble such as the 2D area, equivalent diameter, positions were calculated. The bubble was assumed as the spherical shaped, then the total volume of bubbles and the volume void fraction of the frame can be calculated.

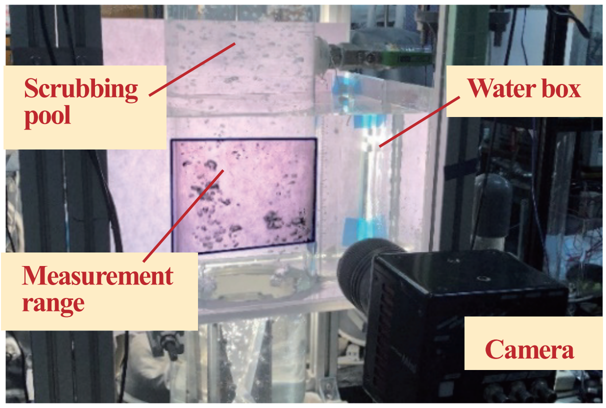
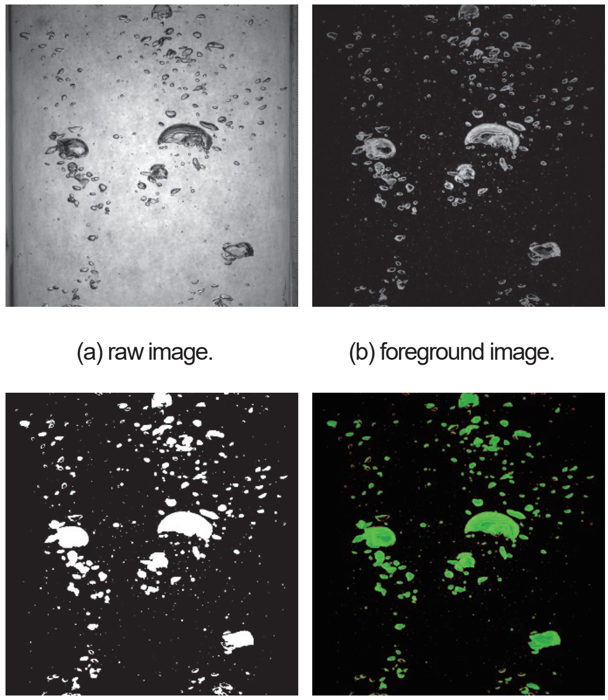


Fig. 2. Set up of visualization measurement.



(a) raw image. (b) foreground image.

(c) binary image. (d) processed image.

Fig.3. Schedule of image processing using Matlab.

The experiment was conducted in different conditions of the air venting flow rate. Figures 4 and 5 shows the bubble size distributions which measured by the visualization method at the air venting flow rate of (a) 27.5 l/min, and (b) 54.97 l/min. It showed that with the increasing of the air venting flow rate, the distributions of the bubble sizes were changed with the high frequency of the small bubble, and it made the increase in the interfacial area of the gas-liquid phases.

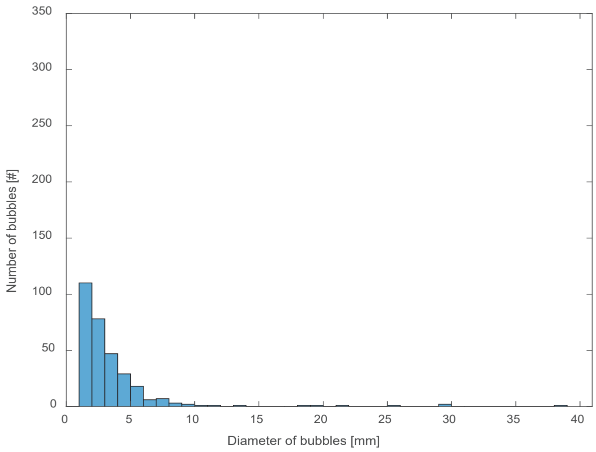


Fig. 4. Bubble distributions at the gas venting flow rate of 27.5 l/min.

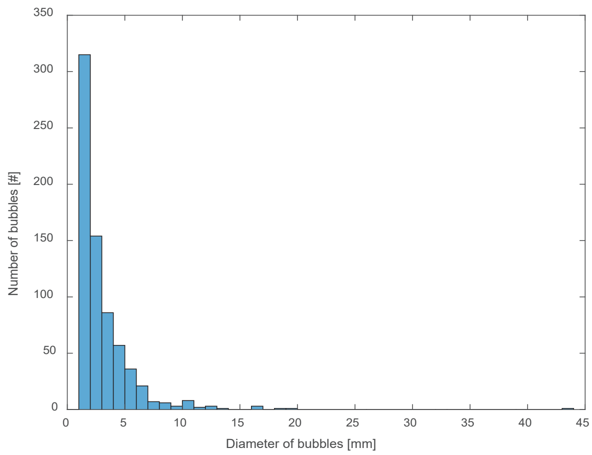


Fig. 5. Bubble distribution at the venting flowrate of 54.97 l/min.

The decontamination factor of the aerosol particles in the scrubbing pool depends strongly on the size of bubbles in the scrubbing pool. The smaller size of bubbles means a higher probability that aerosol particles in the bubbles will come into contact with the gas-liquid interface and then absorbing into the liquid phase. In other words, the interface area of the gas and liquid phase plays important roles to improve the efficiency of the filter. The comparison of the interfacial area of the gas-liquid phase at different condition of air venting flow rate is showed in Fig. 6. The interfacial area of the gas-liquid phase increases with the increasing of the gas venting flow rate.

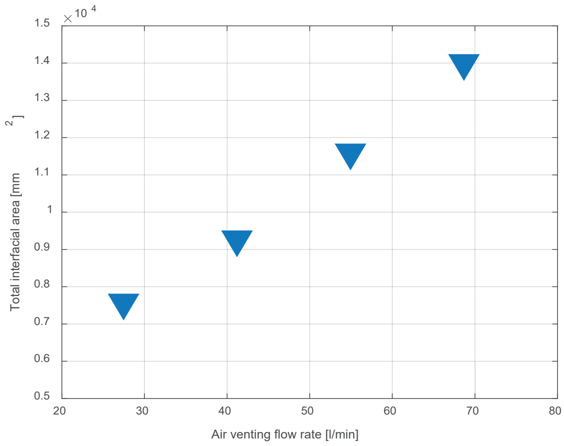


Fig. 6. Dependent of the air-liquid interfacial area on the air venting flow rate.

3. TRAC code analysis

The two-phase flow analyses for the experimental problem were performed using TRAC-BF1 code. Figure 7 Shows the nodding diagram of the TRAC-BF1 model with total of 80 nodes.

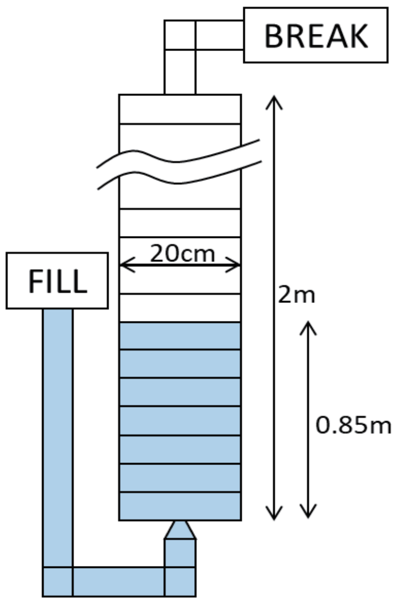


Fig. 7. Nodding diagram of TRAC model.

The initial conditions were set the same as the experimental conditions, such as the temperature is 25°C; the atmospherics pressure was set to the outlet; the initial water level was filled to the height of 0.85m. The boundary condition at inlet is velocity inlet with the gas void fraction of 1.0. The air venting velocities at inlet were set from 0.1 m/s to 0.4 m/s as the same as the experimental condition.

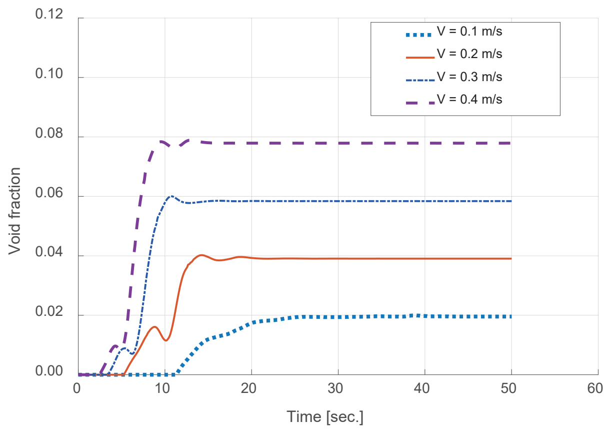


Figure 8. Void fraction of node 15th.

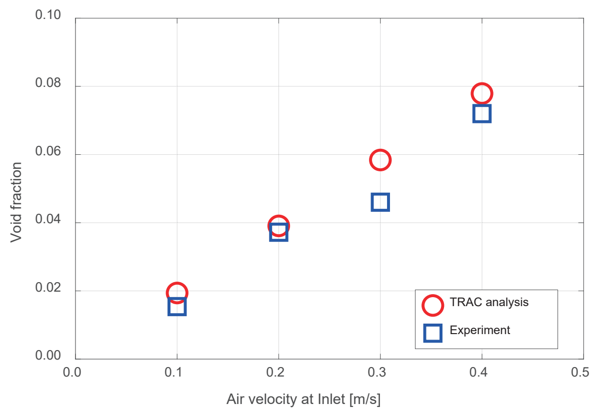


Fig. 9. Comparison of the void fraction between experiment and numerical analysis.

Figure 8 shows the gas volume fraction of the 15th cell of the model which equivalent to the position of the visualization section. It is seen that after 30 seconds; the void fractions of all cases reach to steady state. In order to comparison with the experimental results, the void fraction of the 15th cell was extracted after 30 second. Figure 9 shows the comparison of the void fraction at the height of 0.45 m from the bottom of the scrubbing pool.

4. Conslusions

The experiment was conducted to measure the two-phase behaviour in the scrubbing pool of the wet-type aerosol filter of FCVS. By using the visualization measurement method, the bubble size distribution, bubble velocity can be measured in the low conditions of the air venting flow rate. The measurement result of the void fraction at the low flow rate of air venting was showed that agree with the simulation analysis using TRAC code. This will allow the TRAC code can be used to estimate the improvement designs of the wet-type filter in the next phase of this study.

The experiment also showed that the bubble behavior strongly depends on the venting flow rate. The bubble size becomes smaller, or in other words, the interfacial area of the gas-liquid phases increases with the increasing of the air venting flow rate. And therefore, the decontamination factor of the wet-type filter is increasing with the air venting flow rate.

References

[1] TEPCO, The 5th Progress Report on the Investigation and Examination of Unconfirmed and Unresolved Issues on the Fukushima Daiich Nuclear Accident , December 25, 2017.

[2] Narabayashi, T., Chiba G., Ishii, A. Kitahara, N., Hirai, K., Masuda T., Nakasaka, Y., Sato, N., Endo, K., and Kobayashi, T., Development of high efficiency multi-nuclide aerosol filters for radiation protection during a process of cutting core debris for Fukushima Daiichi NPP, Proceedings of the 27th International Conference on Nuclear Engineering (ICONE27), May 19-24, 2019, Tsukuba, Japan.