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Bubble dynamics with aerosol during pool scrubbing

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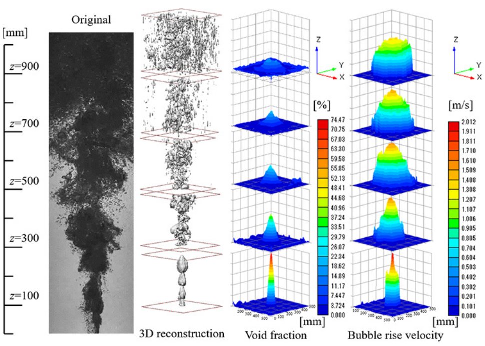
GRAPHICAL ABSTRACT



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ABSTRACT

The aim of the present study is to clarify the flow structure of gas phase jet in pool scrubbing to improve the model written in the MELCOR code. Gas phase jet are injected into a water pool under various flow rates. At first, the gas flow structure were observed with a high-speed video camera in detail. Visualization was performed for each height along the flow direction inside the test section. The bubble size and aspect ratio were estimated from the observed images obtained. Secondly, from the comparisons between the flow model in the MELCOR code and the experimental data, bubble-aspect-ratio was found to be more flattened and widely distributed than the model. Thirdly, in order to understand the flow structure, void-fraction distribution and bubble velocity were measured by using a wire-mesh sensor (WMS) for various flow rate on each height inside the test section. The air-phase speed measured just above the nozzle had a larger value than the swarm velocity estimated in MELCOR. As the bubble rises, the rising speed became more similar to the predicted model. Finally, it is clarified by the comparisons of the visualization results and PIV-analysis results that the interface oscillation of globules leads to the increase of the amount of aerosol transferred from gas phase to liquid phase.

1. Introduction

Once severe accidents such as the Fukushima Daiichi nuclear power plant accident, it is concerned that large amount of radioactive nuclei leaks from the containment vessel of the nuclear power plant. In such situation, those radioactive nuclei exist as aerosol particles in the flow out of the pressure vessel. It is crucial to prevent the radioactive nuclei releasing to the atmosphere. The removal effect of the radioactive aerosol is expressed by the so-called decontamination factor (DF). Various removal effects are expected within the system of the nuclear power plant such as pool scrubbing. The pool scrubbing is the removal effect by the water in the suppression chamber of BWRs and in the

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Nomenclature

a	the major axis of bubble [mm]
b	the minor axis of bubble [mm]
d_B	bubble diameter [mm]
D_O	Nozzle diameter [mm]
Eo	Eötvös number [−]
g	gravitational acceleration [m/s^2]
I_l	signal intensity in the liquid phase [−]
i	mesh number for x-direction [−]
I_g	signal intensity in the gas phase [−]
I_m	signal intensity in the gas–liquid mixture [−]
j	mesh number for y-direction [−]
j_G	superficial velocity for gas phase [m/s]
k	number of samples in a sequence of measurements [−]
Q_S	mass flow rate of air [L/min]
S	bubble area [m^2]
V	volume of bubble [m^3]
Vr	velocity of rising bubble [m/s]
w	gas-phase velocity of WMS [m/s]

Greek symbol

α	void fraction [%]
α'	fluctuation component of void fraction [%]
$\Delta\rho$	density difference of water–gas [kg/m^3]
ρ_L	density of water [kg/m^3]
ρ_G	density of gas [kg/m^3]
σ	surface tension [mN/m]

steam generator of PWRs. If the pool scrubbing is successfully achieved, high DF for the total radioactive aerosol removal is expected.

The MELCOR (Gauntt et al., 2000) code is used in the safety regulation of Japan for the nuclear power plant during the severe accident. The MELCOR code is based on the hydrodynamic model as shown in Fig. 1. Several aspects of the hydrodynamic processes are important to calculate DF. Bubble behavior in a suppression pool during the scrubbing is schematically shown in Fig. 1. Gas leaving a vent becomes large bubbles (globules) that breakup into a swarm of small bubbles in globule breakup region. The swarm rises as bubbles with constant bubble size distribution to the pool surface. The increase of gas volume due to decrease of static pressure as bubble rise is reflected as increase of bubble although bubble division is not considered. As the bubbles reach the surface, most of the bubble are broken up and entrained into atmosphere. Such a phenomenon is called entrainment. Although this process produces droplets at around the water surface, the model does not consider the droplet generation. This is because the frequency of occurrence would be rare, thus, the effect of entrainment was considered to be small (Owczarski and Burk, 1991).

The MELCOR code also expresses the physical situation of aerosol removal process from the gas phase to the water phase as shown in Fig. 1. The DF for the pool scrubbing is estimated based on the mechanism as shown in Fig. 2. On the globule region, removal of aerosol is thought to be done from the collision of particle to the bubble surface, condensation of steam and collapse of large globules. In the swarm region, aerosol in the gas phase is influenced by the bubble rise velocity and bubble motion. Driving force such as centrifugal force, gravitational sedimentation, Brownian diffusion and vapor condensation/vaporization are thought to play a dominant role of the aerosol behavior inside the bubbles. This is the dominant factor to the decontamination of the radioactive aerosol during pool scrubbing.

As predicted in the model, flow dynamics such as swarm/globule rise speed and its transition, flow structure parameter such as bubble diameter and particle transfer behavior affect the driving force of particle. Therefore, it is very important to clarify the two-phase flow behavior and the radioactive aerosol air-water transfer behavior to estimate the DF.

However, the physical model used in the MELCOR code to estimate the DF during the pool scrubbing is not sufficiently verified, yet. Therefore, it is necessary to obtain the experimental information of the aerosol behavior in two-phase flow during pool scrubbing. It is required to obtain the experimental information of the particle behavior in gas phase rising in the water pool. Furthermore, it is also required to verify the physical model used in the MELCOR code to estimate the pool scrubbing of the radioactive aerosol.

Several important studies concerning the pool scrubbing can be seen in literatures. Hashimoto et al. (1991) carried out experiments of the pool scrubbing, mainly focusing on the DF. They clarified the effect of pool submergence and pressure in the vessel on the DF. Dehbi et al. (2001) carried out experiments of the pool scrubbing, mainly focusing on steam ratio and gas flow rate. They also reported that high DF is obtained with increasing the gas flow rate. To date, however, the detail of flow structure and aerosol decontamination behavior was not observed with detailed and individual information which makes it difficult to evaluate the validity of physical model used in previous models.

The final goal of this study is to understand the gas phase jet behavior and aerosol decontamination mechanism to gain enough experimental evidence to make a comparison with the existing physical models. Hence, it is necessary to obtain the experimental information to estimate quantitatively the particle behavior in pool scrubbing. Based on the experimental results obtained, the physical model used in the MELCOR code is verified.

2. Experiment

Fig. 3(a) illustrates the schematic diagram of experimental apparatus. Air was provided from a compressor with various flow rate as the gas phase, and was injected into a rectangular test section (500 × 500 × 3000 mm), which was made of transparent polycarbonate. A high-speed video camera (FASTCAM mini UX100, Photron, Inc.) was installed to record the behavior of bubbles. A backlight illumination using an LED light was applied for visualization. The test section was filled with tap water of 1100 mm depth. Visualization was performed around five regions where the nozzle exit as origin along the

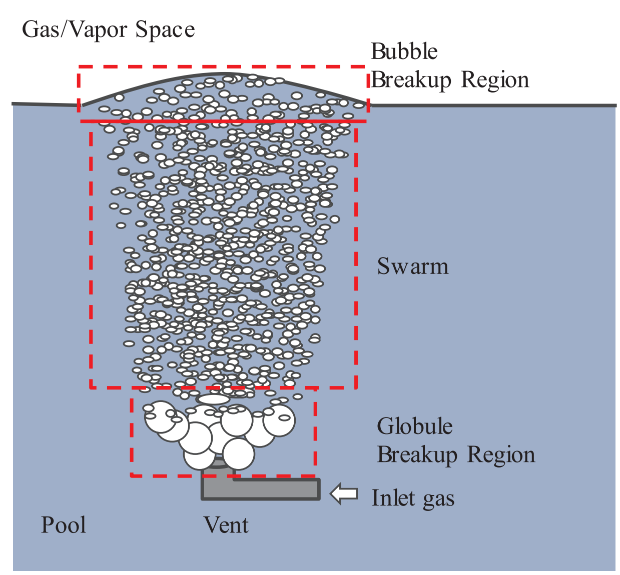

Fig. 1. Schematic diagram of flow behavior during pool scrubbing.