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Temperature dependent fission product removal efficiency due to pool scrubbing

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HIGHLIGHTS

- Pool temperature effects on the FP removal were not clearly concluded in the previous publications.
- It was confirmed that the removal efficiency decreased with temperature around the boiling point.
- A modified empirical formula for FP removal was proposed as a function of sub-cooling temperature.
- DF could be predicted with an accuracy within a factor of 2 with the proposed formula.

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ABSTRACT

The wet-well of boiling water reactors plays important roles not only to suppress the pressure in the primary containment vessel due to steam scrubbing effects during severe accidents but also to mitigate release of radioactive fission products (FP), aerosols and particulates, into the environment. The effects of steam scrubbing in the wet-well on FP removal have been well studied and reported by changing major parameters determining the removal efficiencies, *e.g.*, aerosol diameters, submergence (depth of scrubbing nozzles) and steam/non-condensable gas volume fraction. Unfortunately, the effects of pool temperature on the FP removal were not clearly concluded in the previous publications, though it would be easily expected that boiling in the pool resulted in reduced aerosol removal efficiency. In order to determine the temperature effects on FP removal efficiency, amounts of cesium in aerosols released from scrubbing pool were measured by changing pool temperature in mini and medium scale scrubbing experiments, and then, it was confirmed that the removal efficiency clearly decreased with temperature around the boiling point. Then, a modified empirical formula to express the FP removal around the boiling point temperature was proposed as a function of sub-cooling temperature by applying the effective steam volume fraction, which was designated as the volume ratio of condensed steam in the pool *versus* the sum of input steam and non-condensable gas. By comparing the measured removal efficiency with the calculated, it was validated that the decontamination factor (DF) could be predicted with an accuracy within a factor of 2 with the proposed formula.

1. Introduction

The wet-wells (suppression pools) of boiling water reactors (BWRs) play important roles to suppress the pressure in primary containment vessels (PCVs) during severe accidents to avoid serious damage to the PCVs (Naitoh et al., 2013). At the same time, the wet-wells are expected to remove radioactive aerosols and particles of fission products (FPs, such as radioactive cesium) in the steam effluent as "scrubbing effects", and then, to mitigate FP release from the damaged core into the environment.

Abbreviations: BWR, boiling water reactor; DF, decontamination factor; FP, fission product; KAKEN, KAKEN, Inc., Mito, Japan; LATEX, a stable dispersion (emulsion) of polymer micro-particles in an aqueous medium; NPP, nuclear power plant; PCV, primary containment vessel; SA, severe accident; SIET, SIET SpA., Piacenza, Italy; TUMST, Tokyo University of Marine Science and Technology.

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Nomenclature

a, b, c	constants (a: 8.107, b: 1750, c: 235.0)
D_p	particle diameter (μm)
DF	decontamination factor (–)
F	flow rate (kg/h) [subscripts: s, steam; g, non-condensable gas; CO, carry-over steam]
H_s	scrubbing depth, submergence (m)
P	pool surface pressure (kg/cm^2 g)
S	steam fraction (vol%)
S_{eff}	effective steam fraction (vol%)
T_p	pool water temperature (°C)
T_B	boiling temperature (°C)
α	temperature coefficient to determine steam carry-over rate (1/°C)
ε	steam carry-over ratio (–)
ΔT	sub-cooling temperature (°C)
ρ_W	water density as a function of temperature (kg/m^3)

Many experiments on scrubbing effects have been reported (Berzal et al., 1995; Herranz et al., 2014; Dehbi et al., 1997). Some of them were carried out by changing major experimental parameters systematically, and they have resulted in some valuable empirical formulas to explain the FP removal efficiency as functions of the parameters (Herranz et al., 2014; Hakii et al., 1990; Kaneko et al., 1992). Unfortunately, temperature effects on the removal efficiency have not been clearly reported and some studies concluded that there was no temperature effect on the FP removal. However, when the pool temperature reached the boiling point as a result of a long term wet-well venting operation, major portions of steam from the PCV would easily pass through the water layers in the pool, which would result in escape of FP trapped in the water, and then, a reduction in radioactivity removal efficiency.

Intuitively, it was considered that the radioactivity removal efficiency might depend on sub-cooling of the pool water but this has not been confirmed yet. Only a few publications showed that the boiling condition resulted in a decrease in FP removal efficiency during pool scrubbing (Uchida et al., 2014).

This paper focuses on confirming the effects of pool water temperature on radioactivity removal (sub-cooling effects) in mini and medium scale scrubbing experiments by using non-radioactive cesium iodide (CsI) aerosols as simulated FPs, and then, developing a more realistic empirical formula to express the temperature effects on the removal efficiency for pool scrubbing under severe accident conditions.

2. Previous studies on pool scrubbing effects

2.1. Latest review of scrubbing effects

The dependences of decontamination factors (DFs) for pool scrubbing on major parameters, *e.g.*, particle diameter, submergence, steam volume fraction and gas flow rate, have been well explained by the latest severe accident (SA) codes (Herranz et al., 2014). However, the temperature dependence of DFs has not been satisfactorily evaluated due to lack of suitable data (Herranz et al., 2014).

2.2. Previously reported scrubbing effects and proposed empirical formula

In the early 1990s, the dependences of DF on major parameters were measured by applying a large cylindrical pressure vessel (diameter, 1 m; height, 5 m), a scrubbing nozzle (diameter, 150 mm) and latex particles and the CsI aerosols as simulated FPs (Hakii et al., 1990; Kaneko et al., 1992). Major parameters and their standard values for the experiment are shown in Table 1.

Table 1
Major parameters and their standard values.

Experimental parameters	Symbols	Standard values
Scrubbing depth, submergence (m)	H_s	2.7 m
Water temperature (°C)	T_p	80 °C
Steam fraction (vol%)	S	50%
Particle diameter (μm)	D_p	0.2–1.1 μm
Pool surface pressure (kg/cm^2 g)	P	1.7 kg/cm^2 g

Most of the experimental parameters were controlled carefully and systematically and the DF dependences on the major parameters were clearly obtained except for temperature dependence which could not be evaluated due to poor water temperature control. As a result of evaluation of the experimental data, an empirical formula for DF as a function of major parameters has been proposed, which is shown in Eq. (1) (Kaneko et al., 1992).

$$\mathrm{DF} = A \quad \exp\left(0.19 D_p^2\right) \exp\left\{\left(0.88 + 0.52 D_p^2\right) H_s\right\} \tag{1}$$

$$A = R_s \quad (R_s \geq 1) \qquad = 1 \quad (R_s < 1) \tag{2}$$

$$R_s = \frac{100\left(1 - W_p\right)}{100 - S} \tag{3}$$

$$W_p = \frac{10\hat{\ }\left\{a - b/(c + T_p)\right\}}{\left\{735.6\,(P + 100 H_s \rho_W + 1.0332)\right\}} \tag{4}$$

a, b and c are constants and $a = 8.107$, $b = 1750$ and $c = 235.0$.

Validation of the empirical formula has been confirmed by comparing the calculated results with the measured ones (Kaneko et al., 1992).

2.3. Effects of boiling on the FP removal due to scrubbing

In order to confirm the difference in removal rates of iodine, cesium and hematite particles (average diameter: 1 μm) for boiling conditions and non-boiling conditions, a mini scale experiment (at KAKEN) and a mock-up experiment (at SIET) were carried out and their details were given in the published report (Uchida et al., 2014). Experimental results for room temperature and boiling water conditions are summarized in Fig. 1. DFs for pool scrubbing under boiling conditions were much lower than those under the room temperature for all of iodine, cesium and hematite.

In order to confirm the effects of pool temperature on the removal efficiency, it was not sufficient to show the difference in the removal efficiency for the room temperature and boiling conditions and it was desired to show the temperature dependent removal efficiency of scrubbing around the boiling point temperature.

3. Experiments

3.1. Experiment setups

Two sets of experiments were carried out, one was a mini scale scrubbing experiment done at the KAKEN laboratory and the other was a medium scale scrubbing experiment done at the Tokyo University of Marine Science and Technology (TUMST). The mini scale experimental apparatus used a 5 L inner volume scrubber (Fig. 2), while the medium scale apparatus used a 1 m^3 volume scrubber (Fig. 3). Basic procedures for the experiments were the same as previously reported (Uchida et al., 2014). The only differences in the experiments were continuous supply of scrubbing steam to