Study on Uncertainty of Containment Spray Model using Monte Carlo Simulation

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1. Introduction

Containment spray system is to suppress the pressure build up during Loss of Coolant Accidents (LOCA). The system is also to remove the fission products and the aerosol particles in the containment building, and to supply enormous amounts of water to condense steam promptly after the break of the reactor coolant system pipe. In this paper, new uncertainty estimation methodology of the containment spray system model is introduced. Especially, the uncertainty of the spray system model is important because it influences on dose estimation of the LOCA and has systematic and random error. In this study, Monte Carlo Simulation (MCS) is developed using the Visual Basic to obtain a better uncertainty estimation results. The uncertainty estimation process is based on "International Organization for Standardization (ISO), the Guide to the Expression of Uncertainty in Measurement (GUM)" methodology [1]. And the availability of Monte Carlo Simulation (MCS) is derived from the comparison results between MCS and experiment data.

2. Methods and Results

2.1 Spray Model

In Westinghouse-type Nuclear Power Plants (NPPs), a general spray model was developed to calculate the post LOCA radiation dose. This model was based on the NRC's Standard Review Plan 6.5.2. The spray model was specified by decontamination factor (λ_p) of equation (1), which increased linearly with the amount of fission products removed by spray droplets [2].
This model can be written in equation form as follows:

$$\lambda_p = \frac{1.5HF}{V}\left(\frac{E}{D}\right) \text{ : Decontamination factor} \qquad (1)$$

$$\frac{E}{D}(m^{-1}) = \frac{\lambda_p(hr^{-1})0.01852}{Q(cm^3/cm^2-s)} \text{ : Capture efficiency} \qquad (2)$$

Here, equation (1) can be converted into equation (2).
From these equations, E/D is the capture efficiency which depends on droplet diameter, V is the containment volume, F is the spray flow rate, H is the falling distance of the spray drops, and Q (spray flux) is the volumetric flow per spray droplet surface area.
In this study, Kori unit 1 is selected because Kori unit 1 has the Type-1713A spray model [3] and experiment data is also based on the same spray model. The input variables and the distribution patterns are summarized in Table 1 [3, 4, 5]. Distribution patterns are referred to the experimental studies of Brockmann [4] and Porcheron [5].

Table 1. Input variables and distribution patterns of MCS

Symbol	Description	Value[3]	Distribution[4,5]
$\lambda_p (h^{-1})$	Decontamination factor	3.21	Normal
F(gpm)	Spray water flow rate	1,500	Constant
e	Collision Shape factor	1~4	Log-normal
$Q(m^3/m^2\text{-}s)$	Spray flux	0.0012	Normal
H(m)	Drop fall distance	19.2	Constant
E/D (m^{-1})	Capture efficiency	1~10	Log-normal
$V(ft^3)$	Containment Volume	$1.450X10^6$	Constant
D(um)	Droplet diameter	120 ~ 1500	Log-normal

2.2 Strategy of MCS for Uncertainty Estimation

The ISO/GUM was published in 1993 to establish a new international experimental uncertainty standard. The procedures of ISO/GUM are as follows [1]:

1) Selection of input variable distribution function
2) Generation of input probability distribution
3) Generation of output probability distribution
4) Calculation of statistic specifications from output.

ISO/GUM procedure is summarized as shown in Fig. 1. And MCS is carried out in accordance with Fig. 1.

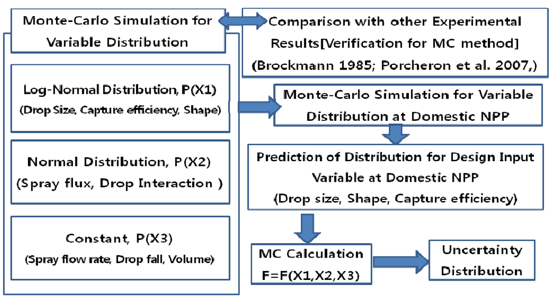

Fig. 1. MCS uncertainty estimation in this study

2.3 MCS Methodology

MCS is conducted using Box-Muller's random equations. These random algorithms are used for anticipating the input variable distributions.
The algorithms are expressed as follows [6]:

- Normal Distribution Prediction

$$\begin{aligned} X1 &= S1 \times \sqrt{-2Ln(R1)} \times \cos(2\pi R2) + m \\ X2 &= S2 \times \sqrt{-2Ln(R2)} \times \cos(2\pi R1) + m \\ X3 &= L \times R3 - 0.5 + m \end{aligned} \qquad (3)$$

- Log-Normal Distribution Prediction

$$X1 = Ln\left(S1 \times \sqrt{-2Ln(R1)} \times \cos(2\pi R2) + Ln(m)\right)$$
$$X2 = Ln\left(S2 \times \sqrt{-2Ln(R2)} \times \cos(2\pi R1) + Ln(m)\right) \quad (4)$$
$$X3 = L \times Ln(R3) \times Skew + Ln(m)$$

In equations (3) and (4),
X1 = the left side of distribution function
X2 = the right side of distribution function
X3 = the range of distribution function
R1, R2, and R3 = uniform random numbers (0~1)
S1 = uniform random numbers (0~0.5)
S2 = uniform random numbers (0.5~1)
L = input variable range
m = input variable
Skew = log-normal shape factor (1~2)
Ln = natural log function

MCS using equations (3) and (4) is compared with Porcheron's experiment results. Uncertainty calculation is conducted by putting the variable distributions of Table 1 into the equations (1) and (2).

2.4 Verification of MCS

In order to show the feasibility of MCS, the comparison results between Porcheron's experimental study and this study are introduced in Table. 2.

Table 2. Comparison between experimental study and MCS

Methods	Statistics	Diameter(C)	Efficiency(D)	Factor(E)
Experiments(A) [5]	Mean	234	60	3.04
	S.D.	2.196	4	0.3
MCS(B) (This study)	Mean	234.01	60.03	3.04
	S.D.	2.191	4.0	0.30
	Iteration	70,000	70,000	70,000
Comparison(F) (B)/(A)	Mean	1.0	1.0	1.0
	S.D.	0.998	1.0	1.0
Error(G) (%) [1-(F)]X100	Mean	0	0	0
	S.D.	0.2	0	0

(A): Porcheron's experimental data, (B): This study,
(C): Droplet Diameter, (D):Capture Efficiency
(E):Droplet Shape Factor, (G): Accuracy of distribution prediction
S.D.:Standard Deviation

Table 2 shows that MCS can perfectly predict the distribution pattern of input variables in comparison with the Porcheron's experimental data. In MCS of this study, the prediction accuracy of the input variables is within 0.2 % (See "Error" of Table 2). These results show that MCS is feasible for uncertainty evaluation.

2.5 Uncertainty Estimation of Spray Model at Kori unit 1

Table 3 shows the prediction results of input variable distribution of Kori unit 1 using MCS of this study. Fig. 2, Fig. 3 and Table 4 show the spray model uncertainties of the capture efficiency and the decontamination factor using MCS of this study. The uncertainties are 1.3% in the capture efficiency and 0.9% in the decontamination factor (See C.E. and D.F. of Table 4).

Table 3. Results of the distribution predictions (from Table 1)

Parameter	λ_p (h^{-1})	e	Q(m^3/m^2-s)	E/D (m^{-1})	D(um)
Mean	3.21	3.01	0.0012	7.09	903.1
S.D.	0.22	0.29	0.0005	0.3	2.2
Iteration	70,000	70,000	70,000	70,000	70,000

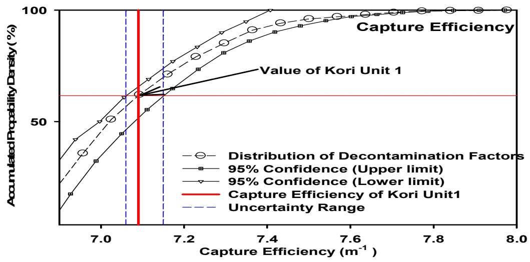

Fig. 2. Distribution of capture efficiency from MCS

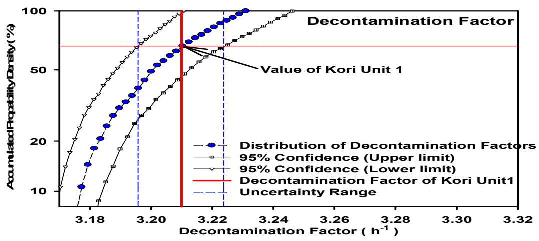

Fig. 3. Distribution of decontamination factor from MCS

Table 4. MCS results of Kori unit 1(from Fig. 2 and Fig. 3)

Item	Mean	S.D.	LCI	UCI	Uncertainty
C.E.	7.09	0.30	7.06	7.15	1.3%
D.F.	3.21	0.22	3.195	3.223	0.9%

C.E.: Capture Efficiency, D.F.: Decontamination Factor
S.D.: Standard Deviation
LCI: Lower Confidence Interval (95%)
UCI: Upper Confidence Interval (95%)
Uncertainty = [(UCI – LCI) / Mean]X100

3. Conclusions

A new methodology of uncertainty estimation using MCS is developed. This methodology can be a useful tool for predicting the distribution of the input variables of Table 1. Also, it is successful for use in estimating the uncertainty of the spray model.

MCS using the ISO/GUM procedure is in good agreement with an error level of 0.2% in predicting the variable distributions. In Kori unit 1, the uncertainty results of capture efficiency and decontamination factor are 1.3% and 0.9% respectively.

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