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Jet pool scrubbing model development for evaluating radioactive aerosol retention in FK2

Sung Il Kim, Byeong Hee Lee, and Kwang Soon Ha
Accident Monitoring and Mitigation Research Team, Korea Atomic Energy Research Institute, (34057) 111, Daedeok-daero 989 beon-gil, Yuseong-gu, Daejeon, Republic of Korea
*Corresponding author: sikim@kaeri.re.kr

1. Introduction

These guidelines include descriptions of the fonts In Fukushima unit 2 (FK2), reactor pressure vessel (RPV) depressurization occurred with safety relief valve (SRV) opening by operators at around 75 h after the earthquake occurrence. At that time, the RPV pressure was over 7 MPa. For several hours thereafter, RPV pressure increase was observed due to the relocation of the corium inside the core. At that time, the drywell and wetwell pressures were lower than 1 MPa, so a large amount of gases were released to the suppression chamber. Core degradation also occurred around this time, and thus fission products (FPs) were included in the gases. It is expected that a large portion of the FPs were removed during the pool scrubbing period in the suppression chamber; the amount of FPs released to the environment was previously calculated with MELCOR 2.2_9607 in the BSAF2 project. MELCOR uses the SPARC90 model to calculate the phenomenon of FP removal during pool scrubbing. Although the model is good for predicting the decontamination factor (DF) in low injection gas velocity areas, its accuracy is not guaranteed in the jet regime. So despite the DF being obtained with the MELCOR calculation in the BSAF2 project, the amount of FPs released into the environment may differ if there is a difference in the DF calculation during the pool scrubbing period. For this reason, the development of a jet pool scrubbing model is essential to accurately estimate the extent or amount of removed FPs [1].

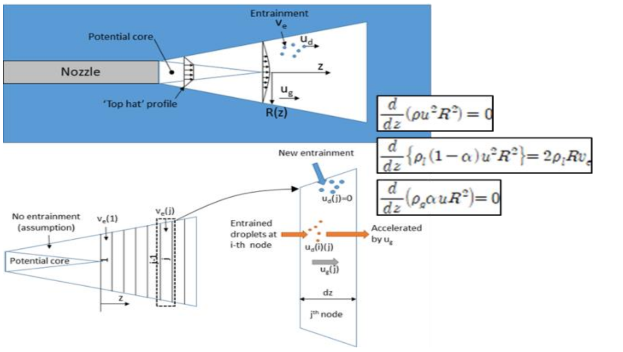

Figure 1. Schematics of the jet region to calculate aerosol removal with water droplets.

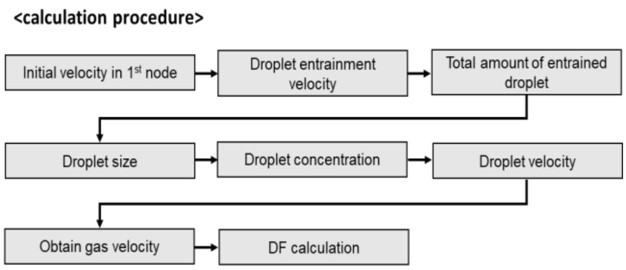

Figure 2. Decontamination factor calculation procedure in the jet pool scrubbing model.

2. Jet pool scrubbing model development

2.1. Jet pool scrubbing model

A jet pool scrubbing model has been developed by KAERI referring to previous studies [2, 3]. In this model, the focus is on the removal of aerosol-type FPs with water droplets inside the jet region. First of all, the potential core is assumed from the nozzle exit to a certain distance, and it is assumed that there is no aerosol removal where there is no droplet entrainment occurring in the potential core region, as indicated in Figure 2. After passing the potential core, aerosol removal by water droplets is considered. The region where the aerosol removal occurs is divided into detailed nodes in the flow direction, with aerosol removal calculation conducted in each node. The calculation procedure is summarized in Figure 3.

Primarily, the initial velocity in the first node at the end of the potential core is obtained from the existing correlation [4], while the droplet entrainment velocity is obtained from the existing correlation using the gas velocity of the node [5]. After that, the total amount of entrained droplets can be obtained from the peripheral wall area of the nodes using the radius of the nodes. The

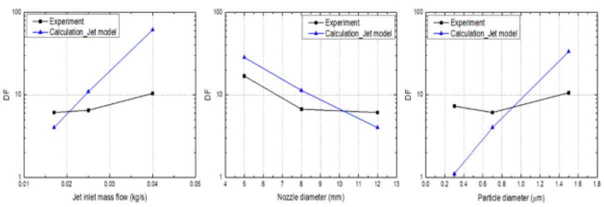

Figure 3. Comparison between experimental data and jet model calculation results

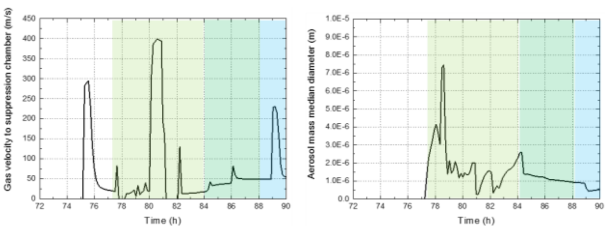

Figure 4. MELCOR results for gas velocity at the nozzle and fission product aerosol size over time.

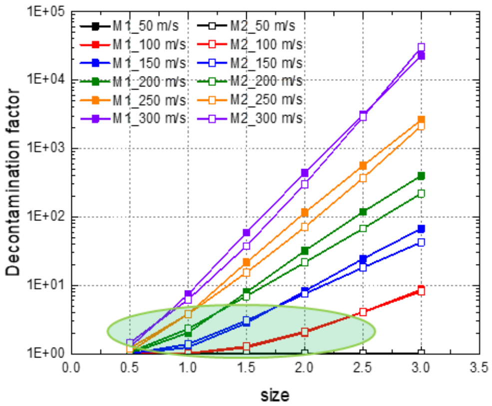

Figure 5. DF calculation during jet pool scrubbing in FK2.

Table 1. DF calculation results from MELCOR and jet models for FK2

Period (h)	DF_MELCOR (swarm & bubble regimes only)	DF_JET Model (jet regime only)
77– 84	High with steam condensation	
84– 88	2– 6	~1.2
88– 90	6– 14	2.0– 3.7

droplet size can then be found from two different options: estimation from turbulent dissipation energy calculation, or estimation from existing correlations [6]. The number of droplets, or droplet concentration, can be obtained from the size of the droplets and the total amount of entrained droplets. The droplet and gas velocities in each node can be derived from the momentum exchange calculation between gas and droplets. Finally, the aerosol DF in the total jet region can be obtained from the integration of the DF in each node [7]. In this jet pool scrubbing model, it is assumed that there is no temperature difference between the gas and pool, and no steam condensation is considered. Each node can have only one velocity, meaning that no velocity profile in the radial direction is assumed.

2.2. Jet pool scrubbing model

In order to verify the jet pool scrubbing model, a jet pool scrubbing experimental results were employed [8, 9]. The target Weber number of the experiment was over 1.0E5, which is the jet regime. The DF was evaluated using the filter method with aerosol sampling at the inlet and outlet of the scrubbing vessel. The scrubbing length was minimized to focus on the jet pool scrubbing effect, and the water level was maintained at around 500 mm. SiO_2 particles were used as simulants of FP aerosols, and non-condensable air was used as a carrier gas in all test cases.

Calculation results from the jet pool scrubbing model were compared with the experimental results. As shown in Figure 3, the DF increased with jet inlet mass flow rate. The overall trend is similar, but the DF was overestimated in the jet model calculation in the case with a high mass flow rate. A high mass flow rate implies a high gas velocity, meaning that more aerosol-type FPs can be captured by water droplets with a longer jet length. In regard to the nozzle diameter test, efforts were made to maintain a constant Weber number while changing only the nozzle diameter, but nevertheless slight differences in the Weber number occurred. From the experimental results, the DF decreased with nozzle diameter. The gas velocity was lower in the larger nozzle diameter test, which is related to a short jet length, and thus the DF decreased with nozzle diameter. With regard to aerosol particle diameter, DF increased with particle diameter from a high collision efficiency (high Stokes number). Generally, as the aerosol particle size increased, the difference between the experimental data and jet model calculation results gradually increased. It was confirmed that some corrections are necessary for certain aspects of the collision efficiency model and droplet entrainment model.

2.3. Application to the FK2 condition

The jet pool scrubbing model was applied to the FK2 conditions. The gas velocity at the nozzle and aerosol particle size were obtained from MELCOR calculation. As it was difficult to specify the DF as a single value due to great fluctuations in the conditions such as gas velocity and particle size over time, calculations were performed for a certain range of gas velocity and aerosol particle size. The calculation results from the jet pool scrubbing model are shown in Figure 5. Two different models for calculating the droplet velocity were considered, a mechanistic model (M1) and empirical correlation (M2), and there was no large difference between them. With increasing aerosol particle size and gas velocity, the DF increased exponentially. It was found that the DF in the FK2 case is located in the green zone in Figure 5. During the period 77–84 h, it is expected that steam condensation occurred actively in the suppression chamber, which makes it difficult to estimate the DF with the jet pool scrubbing model because the model does not consider the steam condensation phenomenon. From 84 to 88 h, the gas velocity was about 50 m/s as indicated in Figure 4, and the DF was very close to 1 as shown in Figure 5. After that time, the gas velocity increased intermittently, which can increase the DF. As stated above, the results obtained from the jet pool scrubbing model only consider the effect of aerosol removal by water droplets in the jet region; accordingly, in order to obtain the total DF, the swarm and bubble rise regions should be additionally considered.

The DF was also calculated with MELCOR calculation using the equation below. DF_MELCOR can be obtained from the FP masses excluding noble gases from the RPV to the wetwell and from the FP

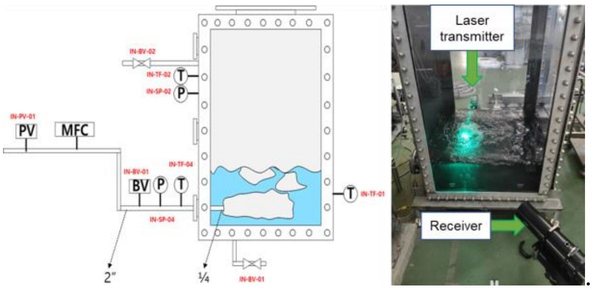

Figure 6. Experimental schematic and photograph of the PDA setup for the water droplet properties in the jet region.

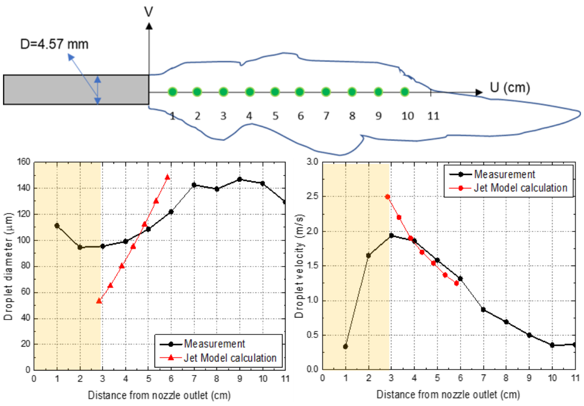

Figure 7. Droplet diameter and velocity in the jet region from PDA measurements.

Table 2. Preliminary test conditions for the droplet property measurements.

Flow rate (lpm)	Gas temp. (ºC)	Gas press. (bar)	Nozzle dia. (mm)	Gas velocity (m/s)	We #	Re #
150	22	1.38	4.57	152.49	1.48E+06	6.32E+04

masses in the liquid phase of the wetwell. During the period 77–84 h, the DF was very high because of steam condensation. After that, the water temperature in the wetwell gradually approached the saturation temperature, leading to a decrease in the DF to around 10 after 84 h. A summary of the DF obtained from the jet model calculation and the MELCOR calculation is presented in Table 1; both of the results should be considered to obtain the total DF during the pool scrubbing period in the FK2 case.

$$DF\_MELCOR = \frac{Inlet\ FP\ mass\ to\ WW}{Inlet\ FP\ mass\ to\ WW - FP\ mass\ in\ WW(liquid\ phase)}$$

3. Efforts to improve the jet pool scrubbing model

The current jet pool scrubbing model contains some uncertainties. One important aspect is to clarify the water droplet properties in the jet region, such as droplet diameter and velocity, because the DF calculation results can vary widely with the properties of the droplets. For this, thermal-hydraulic tests were conducted to measure the droplet size and velocity using PDA, or phase doppler anemometry, as shown in Figure 6. The droplet properties can be measured by transmitting laser light to the droplets in the jet region and measuring the light refracted by the droplets. The preliminary test conditions are given in Table 2, and the position in the jet region where the PDA measurement was performed is indicated in Figure 7. Measurements were taken every 1 cm from the nozzle exit along the nozzle center line. From the measurement data, it was confirmed that the droplet diameter measured at a single point had a size distribution. In addition, droplets were detected in the potential core region, implying that aerosol removal is possible in this region. In contrast to these findings though, the jet pool scrubbing model assumes no aerosol removal in the potential core region and only one droplet size for entrainment. The average values of the droplet diameter and velocity by distance from the nozzle exit are shown in Figure 7 (black lines). The average diameter of the droplets decreased in the potential core region but increased outside this region due to low gas velocity. The measurement data were then compared with the jet model calculation results (red lines in Figure 7). At some points, the jet model calculation results agree well with the experimental data. However, differences are also observable in the droplet diameter area and potential core region. In the future, empirical correlations of droplet size and velocity will be obtained with additional experiments including different jet conditions, and these correlations will be reflected in the jet pool scrubbing model.

4. Conclusion

Jet pool scrubbing model has been developed in KAERI and the model was validated with the related experimental results. Although improvements are needed to increase the accuracy of the model, it applied to calculate the decontamination factor in the suppression chamber of FK2 during the accident, and it was found that the total DF will be higher than it obtained from the MELCOR calculation with considering the pool scrubbing effect. To reduce the unce

rtainty in the droplet size estimation, experiments with PDA have been conducting and preliminary results were obtained. It was found that some corrections will be performed in the model, especially correlation of estimating droplet size in jet. Another issue is the existence of droplet in potential core, because droplets were observed in the potential core with the PDA measurement.

Acknowledgement

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