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Computational Modelling of Spray System Deployment to a Scaled-Down Model of NPP for Severe Accident Mitigation

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1. Introduction

To reduce damage from severe accidents at nuclear power plants (NPPs), a great deal of research has been performed. However, less attention is paid to research that collects and treats radioactive materials that have leaked or escaped from NPP containment. Spray technology has been developed and applied in many industries to remove contaminants in the air because it is cheap and easy to use. Because spray technology has been used in other industries for a long time, it can be applied easily and rapidly to prevent dispersion of radioactive materials from NPPs during severe accident situations. The objective of this study is to develop a numerical model for spray analysis and to investigate the impact of wind (freestream) on the effectiveness of the spray, using a laboratory scale (1/50th) model. [1,2]

2. Methods and Results

To develop a numerical method for analyzing solid particle removal using spray technology, ANSYS CFX, one of the computational fluid dynamics (CFD) tools, was selected and theories, constructed for spray scrubbers, were applied.

2.1. Numerical methods

To determine the behavior of the air and TiO_2 dust, the Eulerian approach was applied. Next, the Lagrangian approach was used to calculate the behavior of sprayed water particles.

2.1.1. The Eulerian approach

The Eulerian approach is usually used in fluid mechanics. Therefore, it is a suitable method for analyzing the behavior of air and TiO_2 dust.

To perform this analysis, it was assumed that all of the materials have same temperature and flow is incompressible in a steady state. In this situation, the energy conservation equations should not be solved, but the continuity and momentum conservation equations were calculated. The k-ε turbulence model was used to solve for the Reynolds stress term, in the momentum conservation equations. [2]

2.1.2. The Lagrangian approach

To analyze behavior of water particles, the Lagrangian approach was used. It was assumed that the shape of water particles are spherical. [3] To treat droplet breakup, the Taylor Analogy Breakup (TAB) model was employed. And, external forces, gravity and drag which act on water particles, were included. [4]

2.1.3. Collection efficiency of a single water particle

There are three mechanisms to collect solid particles in gas: impaction, interception and diffusion. If the diameter of solid particles is larger than 5.0 μm, collection by impaction is dominant and other mechanisms can be neglected. [5] In this study, it was assumed that the diameter of TiO_2 particles is 10 μm. Therefore, to calculate collection efficiency of a single droplet, the following relationship, which just considers the impaction effect, was used. [6]

$$\eta_s = \left(\frac{\psi}{\psi + 0.7} \right)^2 \tag{1}$$

ψ is an inertial impaction parameter defined by the equation.

$$\psi = \frac{\rho_P d_s^2 \left| \overrightarrow{U_F} - \overrightarrow{U_P} \right|}{9 \mu d_P} \tag{2}$$

where d_s is the diameter of a solid particle and μ is the viscosity of the fluid around the particle.

Solid particles released from a containment building can be captured by a single droplet, and it is possible to calculate the quantity of solid particles captured by a single droplet. This relationship is represented by the following equation (3)

$$N_C = \eta_s \frac{\pi d_P^2}{4} \left| \overrightarrow{U_S} - \overrightarrow{U_P} \right| \frac{N_S}{dV} \tag{3}$$

where U_s is the velocity of a solid particle, N_s is the number of solid particles, and dV is the element volume.

The following equation (4) represents the total removal efficiency in this system.

$$\eta_{total} = 1 - \frac{\dot{m}_{out,solid}}{\dot{m}_{in,solid}} \tag{4}$$

2.1.4. Mesh and boundary condition

In order to determine flow and sprayed particle behaviors, meshes were defined for use in the CFD. The geometry was based on an experiment equipment currently being constructed (1/50th scale of the containment building of APR-1400) at KAIST. A reduced scale was selected because it is difficult to experiment repeatedly on a full scale, constructed model. This mesh was generated with a hexahedron shape from ICEM CFD software, which can compose of a variety of mesh size and types.

Fig 2 represents the boundary conditions for this analysis. On the “inlet” boundary, the velocity of air was set to be 0.5, 1.0, 1.5 and 2.0 m/s. On the outlet boundary, the gauge pressure was 0 kPa. “Ground” boundary had no slip condition, and “side” boundary had a free slip condition because the effect from the side wall is small enough to be neglected. On the “dust release” boundary region, TiO_2 particles were released at 1 g/s and 10 m/s. Water particles were sprayed at 60 cm (Case 1) and 30 cm (Case 2) from containment using a particle injection model. Additional experiment design details include, a 30^0 nozzle angle (from ground), a water flow rate of 1 L/min, and a sprayed angle of 55^0. On the containment wall, it was assumed that all of the water particles lost their momentum because of inelastic collisions. On the “plate” boundary, water particles were absorbed.

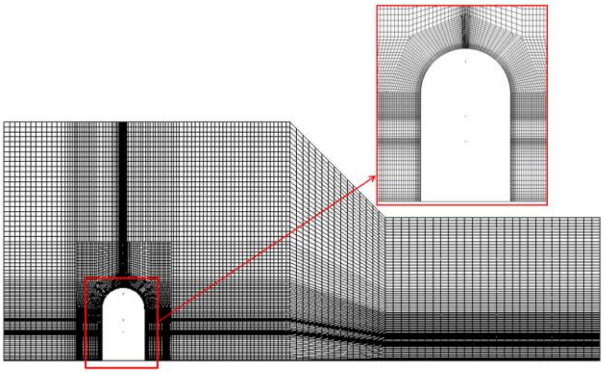

Fig. 1. The mesh for CFD analysis

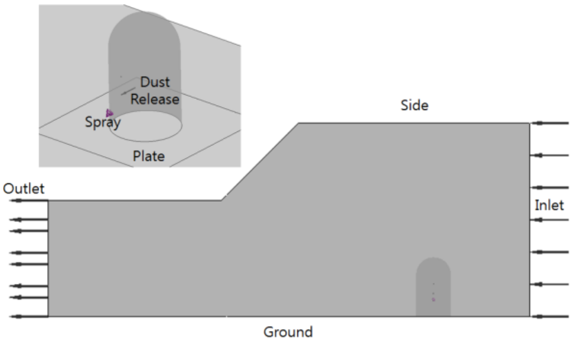

Fig. 2. The boundary conditions for CFD analysis

2.1.5. Convergence criteria

The RMS residuals and imbalances of momentums and mass are the two main factors in defining convergence criteria. When the RMS residuals are lower than 10^{-4}, and the imbalances are lower than 5%, convergence is achieved.

2.2. Results and discussions

2.2.1. Mesh dependency test

Fig 3 represents the results of the mesh dependency test. When the number of elements is about 1.4 million, collection efficiency is almost converged (straight portion of red line in figure). However, the removal efficiency is almost independent from the number of mesh. Therefore, in order to analyze the effect of freestream, it is reasonable to use a mesh which has about 1.7 million elements.

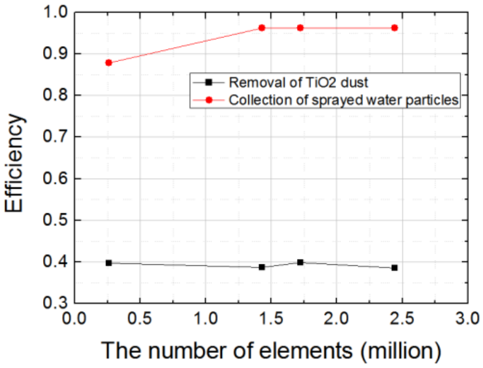

Fig. 3. The results for mesh dependency tests

2.2.2. The results of Case 1 when the spray position is 60 cm from the containment wall

Fig 4 shows the change in removal efficiency of TiO_2 particles and the collection efficiency of water particles when the spray position is 60 cm from the containment wall. With a 0.5 m/s velocity of freestream, the removal efficiency is ~40%. If the velocity of freestream increases, the removal efficiency decreases until 1.5 m/s. However, with a 2 m/s the velocity, the removal efficiency rises about 10 % compared with the result of 0.5 m/s. This is because the effect of increasing the relative velocity between water particles and TiO_2 dust is larger than other analyzed velocities.

The collection efficiency of water particles decreases sharply following an increase in the freestream velocity. With a 0.5 m/s freestream velocity, the collection efficiency is ~96%, but, with a 2.0 m/s freestream velocity, the collection efficiency is ~33%. This value is too low to prevent dispersion of radioactive materials. If the freestream velocity is larger than 1.0 m/s in 1/50th scale, the collection efficiency of the water particles is very low. However, velocities greater than 1.0 m/s will be tested on a real scale to determine the actual efficiency that can be achieved.

2.2.3. The results of Case 2 when the spray position is 30 cm from the containment wall

The removal efficiency of TiO_2 particles and collection efficiency of water particles are presented in Fig 5, when the spray position is 30 cm from the containment wall. When the velocity of freestream is 0.5 m/s, the removal efficiency is ~16%. If the velocity of freestream increase, the removal efficiency increases almost linearly. In this study, the velocity of freestream was analyzed up to 2 m/s, the removal efficiency increases to ~30%. However, the overall removal efficiency of TiO_2 particles is lower than the results for Case 1. Because the area sprayed by water particles, around the containment, is a three dimensional volume (as seen in Figures 1 and2), it makes sense that Case 1, which covers a greater volume, has a higher removal efficiency than Case 2 which covers a smaller volume.

In this case, if the velocity of freestream increases, the collection efficiency decreases. With a 0.5 m/s freestream velocity, the collection efficiency is ~98%. When the velocity of the freestream becomes 2 m/s, the collection efficiency decreases to ~78 %. Finally, the overall collection efficiency of water particles is higher in Case 2. This is because the effect of freestream is smaller in Case 2 due to the shorter distance of the spray nozzle to the containment.

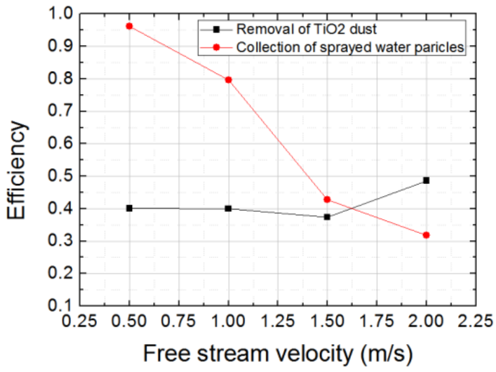

Fig. 4. The graph of case 1 results when the spray is positioned at 60 cm from containment wall.

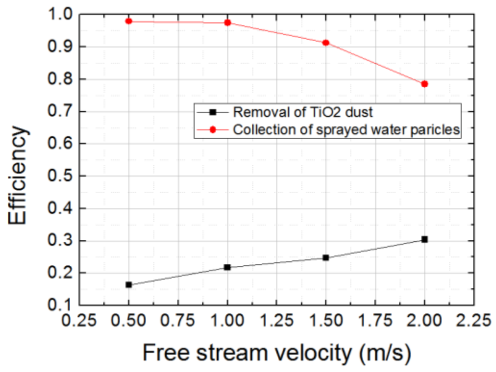

Fig. 5. The graph of case 2 results when the spray is positioned at 30 cm from containment wall.

3. Summary

In this study, a numerical method was developed to analyze the performance of spray to capture particles. To construct the numerical method the following models and techniques were used: ANSYS CFX was selected to perform CFD analysis, the ICEM CFD was used to define meshes, the Eulerian and the Lagrangian approaches were coupled to solve for the behaviors of fluid flow and water particles, TAB model was applied for the breakup of fluid particles, and mathematical models for a spray scrubber were used to analyze the removal of solid particles by sprayed water particles. In summary:

1) If the number of mesh elements is more than 1.5 million, the removal efficiency of TiO_2 dust and the collection efficiency of water particles are independent from the number of the elements.

2) When the spray position is 60 cm from the containment wall, the removal efficiency decreases a little following an increase in the freestream velocity. This is true up to 1.5 m/s, until the removal efficiency increases when the freestream velocity rises above 1.5 m/s. The collection efficiency of water particles sharply decreases following an increase in the freestream velocity.

3) If the spray is closer to the release location, the collection of water particles increase, but the removal efficiency of TiO_2 decreases. Therefore, spray nozzle distance from the containment should be located far enough to remove the toxic materials. At this point it is expected that controlling the nozzle angle from the ground in conjunction with changing the velocity of freestream will lead to an optimal deployment.

4. Future works

This numerical model will be further improved by considering order mechanisms such as diffusion and interception. This model will be validated and modified through comparison with experimental data. After the validation, use of spray technology will be investigated for a real scale problem based on the use of the numerical model and the dimensionless analysis. Implementation of spray in this case will be based on the use of fire truck or fixed spray system.

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